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THE CHARACTERISTICS OF THE VACUUM SPARK.

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Thesis presented for the Degree of
Doctor of Philosophy of the University of
Glasgow.

June, 1954.

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1. The High Vacuum Spark: Introduction and Historical Survey.

1.1. Introduction.

Electrons can be extracted from cold metal surfaces by high electric field strengths. The phenomenon is known as field or auto-electronic emission, and in 1928 Millikan and Lauritzen (1) introduced an empirical formula governing the emission. This was

$$I = C \exp. (-B/V)$$

where I is the electron current,
 V is the extractive field,
and C and B are constants.

The classical theory of that time (2) failed to provide a field emission mechanism and in 1928 Fowler and Nordheim (3) produced a theory based on wave mechanics. This theory has been successively improved until it now agrees with the empirical results within the limits of experimental error (4).

If the voltage between electrodes in high vacuum is raised, the field emission current will rise, and at a certain point a sudden increase of many orders of magnitude will take place. This phenomenon is known as high vacuum breakdown and is the subject of the present study.

The prevention of high vacuum breakdown is of importance in certain high voltage equipments such as transmitting valves, X-Ray tubes, magnetrons and accelerator tubes.

A considerable volume of work has been carried out on vacuum breakdown but with various types of electrode geometry,

material, and surface condition. A great deal of the available information remains uncorrelated, and with this in mind the following historical survey has been drawn up. The survey concludes with a summary of the various proposed mechanisms of breakdown and a correlation of the available results with these mechanisms.

The text, (sections 2, 3 and 4), which follows the historical survey, describes the experimental techniques and presents the data obtained. The conclusions, other than those necessary for an explanation of the test procedure, are reserved until the final section.

1. 2. Historical Survey.

The high vacuum spark and arc were first mentioned in published papers in connection with spectrographic studies, and as early as 1897 Wood described what was apparently a high vacuum spark. In these studies, (5,6,7,) the spark or arc was used as a spectrographic source in the determination of the spectrum of the electrode metal.

In 1918, Millikan and Sawyer⁶ described experiments which had taken place in 1905 on high vacuum breakdown across gaps of one millimetre or less. 'Hot metallic sparks' were obtained at gradients of about 150 KV/mm. It was noted that the breakdown voltage rose with continued sparking, and that there was a fall in breakdown voltage to about the original value if the electrodes were left for some time. This led the authors to suggest the dependence of the spark potential on a surface condition.

In 1922, Hayden (8) wrote of breakdown between highly polished molybdenum spheres. The bulb was baked while evacuated, and the spheres were outgassed by heating to incandescence by electron bombardment. The voltage (sixty cycles per second) to break down the gap of 3.06 mm. was 213 KV., or a maximum macroscopic surface gradient of 123.5 KV/mm.

Piersol, (9,10), in 1924, described discharges between hemispherical molybdenum shells which were 0.23 mm. apart. The tube was baked at 500°C before sealing off, and prior to testing, the electrodes were heated to 1400°C. A critical gradient of 540 KV/mm. was obtained.

In 1926 the G.E.C. Research Staff (11) mentioned breakdown phenomena in experiments on electron field emission from a filamentary cathode to a disc anode, and described how on occasion the discharge took place via the glass. They suggested that the transitory effects might be due to sodium. A resistance in series with the electrode system had a value of 1-10M Ω and breakdowns were obtained at fields higher than 440 KV/mm.

Eyring, Mackewan and Millikan, (12) in 1928, published a paper in which they stated that it was possible to condition their wire cathode so that a surface field strength of 400 KV/mm. produced no current at all.

In the same year Hull and Burger (13) described vacuum breakdown phenomena..

Heavy discharges were passed between 'solid tungsten electrodes' 2 mm. apart. Cathode Ray Oscillograph studies showed that the current started as a 'pure electron discharge', but soon changed to a tungsten vapour arc. The arc voltage was less than 1,000 and the discharge current was as high as 20,000 amperes. As soon as the discharge ceased, the tungsten vapour condensed and the breakdown voltage returned to its original value. The time lag in passing from pure electron to arc discharge was less than 10^{-7} seconds. The time lag in reverting to electron discharge was between 1 and 10 microseconds for heavy current discharges. The surface gradient necessary for breakdown was about 50KV/mm. for tungsten and 10KV/mm. for carbon.

Also in 1928, de Bruyne (14), mentions that if the voltage was taken too high during his field emission measurements (of the order of microamperes), a bright star would momentarily appear on the cathode, and thereafter a new emission characteristic was obtained.

In the same year Tomaschewsky (15), described experiments carried out at Leningrad on "The Insulating Strength of High Vacuum". Experiments at lower voltages, up to a few thousand, confirmed the results of Millikan et al. (11,12) for well outgassed electrodes. At higher voltages experiments were carried out with various metals and shapes of electrodes - disc type and crossed wires at spacings of 1mm. Outgassing in general, consisted of either baking the tube at 400°C or bombarding the electrodes by electrons and gettering with alkali metal.

Tomaschewsky found that for these different electrodes the discharge started about 40KV with intense X-Ray fluorescence of the vessel walls. In another set of experiments, electrodes of nickel, iron, and various steels, were outgassed by preheating to $1,000^{\circ}\text{C}$ in a vacuum oven and then by application of high voltage when set up in the system. With a gap of 3.5mm. the discharge started at 130-140KV. Tomaschewsky noted that the behaviour of steels depended on their carbon and sulphur content - the higher the content, the lower the discharge voltage.

A periodic appearance of gas, which was indicated by a glow in the gap was noted when using steel electrodes, indicating, it was thought, a diffusion of gas from the inner layers of the metal. This was noted at a certain stage in the outgassing when the electrodes were subjected to 120-140KV. Gas would start to appear at the electrodes after 20-50 seconds, and would be pumped away - the gap again becoming dark. This cycle could be observed over many hours, occurring at regular time intervals; the shortest of which was about five minutes. This phenomenon usually disappeared with further outgassing.

Certain circumstances made Tomaschewsky suggest that the breakdown was due, not to the field strength on the electrode surfaces, but to the total voltage. This seemed to be verified by the fact that in an experiment with one half of an electrode removed, the discharge characteristics were the same as with the electrodes whole. He cited the results of del Rosario (16), who apparently found that the discharge current was the same for different fields. Del Rosario's

results were disproved later (17). Tomaschewsky observed that outgassing was impaired little by allowing the system to stand for a time at atmosphere. It was concluded from this work, that with simple methods of outgassing and normal engineering materials, a breakdown strength of 40KV/mm. can be obtained.

In 1930, Compton and Langmuir (78) mentioned that in 1914 (Coolidge) and 1922 (Coolidge and Langmuir) it was observed that when field currents from a point cathode in high vacuum were raised to several milliamperes, incandescent sparks were shot out from the cathode in the general direction of the disc-shaped anode. These particles described sharply curved paths, convex on the side towards the anode, so that most of them did not strike the anode. Many of these particles, when they struck the anode or bulb, were seen to rebound. It was suggested that this effect was probably caused by local heating resulting from the enormous current densities at the emission spot. Particles leaving the cathode had a high negative charge and were attracted towards the anode. Because of their high temperature, however, they emitted electrons and so became positively charged, and were repelled from the anode. Consideration of the temperatures attainable at the point, showed that for intensities of as much as 10 amperes per cm^2 the temperature difference produced would be only about 1° , and it appeared probable that the particles originated at surface points which were not in good electrical and thermal contact with the body of the cathode.

Bennett, in 1931(19), made some interesting observations regarding breakdown. His study was on the discharge between unconditioned spheres with a series resistance of $10M\Omega$. "It was established that with fair polish and purity, the first emission always began at much higher field strengths and suffered a sudden spontaneous increase of large order of magnitude at still higher fields, i.e. "breakdown", than the fields at which emission was drawn subsequently." He found that on occasions there would occur a sudden large order increase in current which behaved like premature breakdown. It would just as suddenly disappear, accompanied by a distinct click of the glass, as if a metallic particle had hit it. This seemed to indicate that foreign particles, either from the anode or some other part of the tube, could fly to the cathode, adhere, give emission, and be torn from the cathode leaving no scar which would give measurable emission.

Bennett also found that, using a copper cathode and anodes of molybdenum, aluminium, chromium and magnesium, the lowest measurable current following breakdowns occurred at fields much higher than with a copper anode. It would appear that the auto-electronic emission was from a particle torn from the anode and adhering to the cathode. If alternatively the breakdown was due to rupturing of the copper cathode surface, it would be necessary to suppose that the relatively lower currents using one of the above four metals as anode was due to "beating down of the ragged edges by positives from the anode."

(The term 'positives' was presumably intended to cover either positive ions or larger particles of anode material with a positive charge.) This possibility was further supported by the fact that, after prolonged auto-electronic discharge, the white colour of the anode metal was distinguishable as a small spot at the emitting point on the copper cathode.

Also in 1931, a paper by Snoddy (20), described impulse breakdowns carried out using pure copper electrodes. Rotating mirror photographs of the discharge showed a luminous spot at the anode lasting 1 to 4×10^{-7} seconds, and a luminous spot at the cathode starting slightly later (1 to 2×10^{-7} sec.) than at the anode and continuing throughout the discharge. The anode did not remain luminous unless the current was very large. The breakdown had two stages - the first was a pure electron discharge lasting less than 5×10^{-7} second which was followed by a low-voltage, copper vapour arc. The current-voltage characteristic of the high voltage stage followed the well known law for auto-electronic emission. For the two gaps investigated the areas of emission were calculated to be approximately $3 \times 10^{-3} \text{ cm}^2$ and $1 \times 10^{-5} \text{ cm}^2$ and confirmed by microphotograph. It was shown that in each case the anode spot at the time of breakdown reached a temperature of approximately 2600°C . Current densities ranged from 10^8 amp./cm^2 at $5 \times 10^{-7} \text{ sec}$. after breakdown to $8 \times 10^3 \text{ amp./cm}^2$ at which value the arc extinguished.

A further paper by Bennett, in 1932 (21), described breakdown and cold emission experiments. He concluded as a result of/

of this investigation, which used a magnetic field to deflect electrons away from the anode region opposite the point cathode, that the breakdown during cold emission was due to a stream of positive ions with high velocity. These were produced by an initially small electron current striking the anode.

In the same year (1932) Beams (22), described high vacuum discharge experiments involving a very high anode field and a very low cathode field. From the voltage at which the discharge occurred he deduced that the breakdown phenomenon was initiated by positive ions from the anode, and suggested that the source of the positive ions was alkali ions adsorbed on the tungsten surface.

Gossling (23), described investigations on high vacuum breakdown as it affected high power transmitting valves. He used an oscillatory circuit as his high voltage supply and tested actual valves. During the initial stages the discharge had a high but progressively decreasing resistance, and a certain amount of energy had to be available in the supply condenser before breakdown could be completed. When the breakdown was artificially encouraged by a pilot discharge across loose contacts, it was found that the initial expenditure of energy was no longer required and the "flashing voltage" could be very low. It was observed that field emission up to a few hundred microamperes had little, if any, effect on the breakdown. The initial transition stage of the discharge lasted for 2×10^{-7} sec. to 4×10^{-7} sec. which is in good agreement with Snoddy's (20) figure of 5×10^{-7} sec.

The time of flight of positive ions for the system was about 10^{-7} second.

A valve would sometimes break down a few minutes after the application of the voltage, and such time lags were sensitive to voltage. A three per cent increase of potential decreased the time lag approximately in the ratio 10 to 1. The field emission current persisted if a series resistance of about one megohm was connected close to the tube, whereas the 'flash arc' was either suppressed entirely or considerably reduced.

Gossling suggested that the discharge might be due to large field emission currents from points produced by some form of surface rupture under the influence of the applied fields. This theory is attractive since such yielding requires time, (24, 25.)

It was also suggested that if a field emission current above a critical value gave rise to a breakdown, and the current was required to exist for only a very short time, an explanation might be found on the basis of the Schrot effect (26, 27).

This effect, sometimes known as the Schottky effect, is a rapid fluctuation in field emission current experienced in valves.

In 1933, Van Atta, Van de Graaf and Barton (28), suggested that the breakdown within their high voltage discharge tube, which operated at 300KV, was due to ionisation at the electrode surfaces caused by the impacts of ions, electrons, and photons. They proposed that if

- 1 electron on the anode produces A. positive ions,
- 1 electron on the anode produces C. photons,
- 1 positive ion on the cathode produces B. electrons,
- 1 photon on the cathode produces D. electrons,

then there is breakdown if $AB + CD \geq 1$. It was suggested that breakdown by such mechanisms could be eliminated by screening the electrodes with grids at such a potential as to trap the secondary electrons and ions.

In a letter to the Physical Review, Mebs (29) described some breakdown studies to determine the effect of series resistance. He used extremely fine outgassed points of tungsten for his cathode, and found that when a series resistance of $1.8 \times 10^9 \Omega$ was used, a typical breakdown occurred, but no rupture of the point could be found afterwards using a microscope. When $2 \times 10^6 \Omega$ was used, rupture of the point occurred at the same value of current, and the deformation of the cathode was easily seen. Emission could not be produced from copper cathodes without severe rupture when a resistance of 10^6 ohms was used, but when a resistance of 10^9 ohms was used no rupture could be found. "Hence it is proven that breakdown due to disruption of the cathode surface is not produced by the electric stresses due to the field, but instead is a function of the current."

In 1934, Beams (30) described experiments on the impulse breakdown between a spherical steel anode and a mercury plane cathode. The field at the cathode when breakdown occurred varied between 65KV/mm. and 180KV/mm., depending on the purity of the mercury pool. In all cases the value of the field for the discharge was critical (i.e. a few per cent change in field caused a change from no discharge to violent discharge). A rotating mirror photograph at breakdown showed luminosity

starting at the anode and reaching the cathode 2×10^{-7} seconds later. He found that allowing dry nitrogen or hydrogen, at about 10mm. of mercury pressure, to come in contact with the mercury cathode for a few minutes had no appreciable effect on the discharge potential. Water vapour or impurities such as grease vapours lowered the discharge potential markedly. He estimated that the current density to start the discharge was about one ampere per square centimetre.

In the same year Chambers (31), described breakdowns between concentric cylinders. The tungsten wire cathode was well conditioned by heat treatment, and currents as small as 10^{-11} amperes could be recorded. Current first flowed at approximately 10^{-4} amperes- that is, breakdown occurred before measurable field emission current was obtained. Four different wire cathodes were used in the experiments - two of 0.5mm. diameter and two of 1.6mm. diameter. The breakdowns after heat treatment all occurred within 10% of the average voltages stated for the different wires, and also for different occasions with the same wire.

The average values were,

0.5mm. diameter wire	-	11,000 volts	(260KV/mm. at the wire surface)
1.6mm. " "	-	23,000 volts	(210KV/mm. at the wire surface)

It was not known whether rupture at breakdown was caused by electrostatic forces at the surface of the wire or by bombardment of the cathode by positive ions. These ions might be produced by the ionisation of the residual gas in the space

between the electrodes, or by electrons striking the anode. In either case, the electrons would have to originate as cold emission from the cathode. If the field necessary for this cold emission was obtained by means of small projections on the surface of the wire, then a layer of vapour adsorbed on the wire surface would tend to smooth over these projections, and make the potential necessary for the breakdowns very much larger. Consequently, mercury vapour was allowed to enter the tube by removing the liquid air from the cold trap. After the trap had attained room temperature the liquid air was replaced, and the system left to stand until the pressure was again down to 10^{-7} mm. of mercury. The 0.5mm. wire was used and breakdown occurred at 10,200 volts, which is in the range of the breakdown voltage attained with clean wires. Chambers therefore assumed that the surface was already smooth and the measured field was very nearly the true field. Since the surface was smooth, then the fact that the breakdown occurred in the neighbourhood of one particular point was explained by the concentration of the origin of the positive ions. He thought it easier to conceive of the anode giving off ions from one preferential area than residual gas ionising in one preferential volume, and therefore concluded that the positive ions were produced at the anode by electron impact. If the breakdown had been caused by electrostatic forces it would have occurred at a much lower voltage with mercury on the wire than when clean.

There was no breakdown at 25,000 volts with the 0.5mm.wire (a cathode field of 600KV/mm.) when a resistance of 8×10^{-11} ohms

was put in series with the electrode system. The resistance was then successively reduced by factors of three, and on each occasion the voltage taken up to 25,000 volts without breakdown. Finally, when the resistance was reduced to 3×10^9 ohms, the breakdown occurred at 11,500 volts (a cathode field of 270KV/mm.). The limits between which the breakdown began to occur were 2.5×10^9 ohms and 7×10^9 ohms.

Further evidence that the ions causing the breakdown come from the anode was given by the following experiment. By means of an induction furnace the cylinder was heated bright red for 1 hour. No breakdown occurred when the voltage was then raised to 25,000 volts (0.5mm. wire). After several hours the breakdown occurred at 11,000 volts. Langmuir had shown that a surface layer of adsorbed gas forms on a clean tungsten surface in about 1 hour at 10^{-8} mm. of mercury. From this it appeared that the presence of adsorbed gas on the anode is necessary before breakdown can occur.

The following mechanism was suggested to explain the breakdown phenomenon. The heating of the wire smooths the wire to such an extent that measurable currents due to cold emission do not flow. However, electron currents below the limits of the measuring apparatus do flow. A certain number of positive ions are formed for each electron striking the anode. The positive ions so formed are accelerated through the potential difference and bombard the cathode. When the potential and the number of ions are both large enough a rupture of the cathode occurs. Since the binding of the atoms of the adsorbed gas is much less

than the binding of the atoms of the anode itself, it seemed natural to assume that the ionisation coefficient is larger when an adsorbed layer is present than when the metal is clean. Such a view explained the increased ease of rupture in the case of an adsorbed film of gas.

In 1935, Anderson (32) described experiments on the breakdown between sphere and disc electrodes at a pressure of approximately 10^{-5} mm. of mercury. He found that the most effective means of conditioning was to run a discharge in hydrogen between the two electrodes at a current density of about 0.25 amp./cm.² for three minutes. The voltage source was an electrostatic generator but it was found that sparking with a more powerful source gave similar breakdown voltages which were, however, accompanied by serious surface roughening. Results were usually reproducible to within a few per cent, but the lower portion of the B.D. -gap curve would be found to have shifted somewhat as a consequence of the electrode treatment represented by the higher voltage spark-overs. He found that although the curve of breakdown voltage to gap was approximately linear over the initial region below one millimetre, there was a very definite flattening above this spacing which he called the "Total Voltage Effect" and attributed to positive ions (see graph 1).

He found that a formula

$$V = \frac{590 \cdot d}{0.77 + d} \text{ KV (d in cm.)}$$

held approximately for the breakdown voltage and his figures for 1mm. gaps for various materials were -

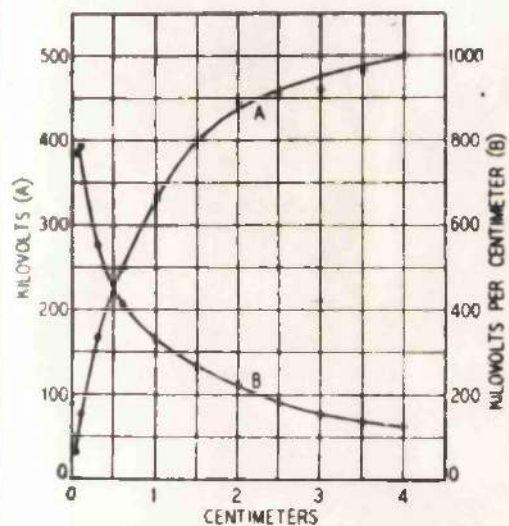


Fig. 1. Break-down voltage (A) and break-down gradient (B) versus inter-electrode distance

Graph 1 (Ref. 32)

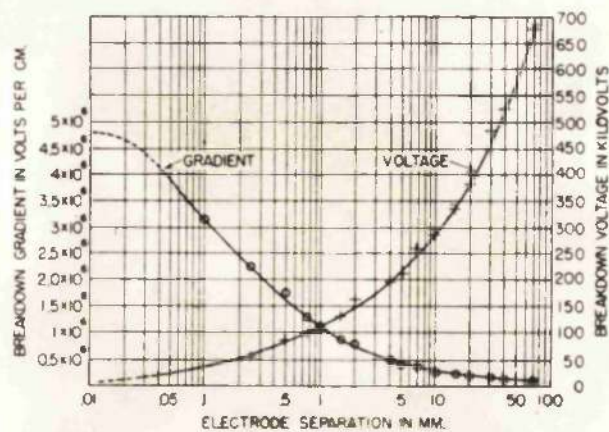


Fig. 2. Breakdown voltages and gradients between 1" stainless steel ball and 2" steel disk in vacuum.

Graph 2 (Ref. 39)

<u>Material</u>	<u>Breakdown Voltage (KV) for 1mm. gap.</u>
Steel	122
Stainless Steel	120
Nickel	96
Monel	60
Aluminium	41
Copper	37

If a steel cathode and a copper anode were used, and a voltage near the breakdown value applied, traces of copper would be found on the cathode, and the gap thereafter exhibited the characteristics of a copper gap.

Anderson considered that this showed that positive ions crossed the gap and the importance of the anode material. To determine what proportion of the total conduction was attributable to positive ions, Anderson used two spherical electrodes - one hollow and thermally insulated, and the other solid and in good thermal contact with a heavy metal mass. The rate of rise of temperature of the hollow shell as anode was several hundred times that as cathode, indicating that only a small fraction of the total conduction was directly due to the positive ions.

Quarles published a paper (33), in 1935, on the field emission from liquid mercury. He described impulse breakdown tests up to 85KV between a spherical molybdenum anode and a mercury cathode - the purity of the mercury could be varied by repeated distillation. The work function at each mercury surface condition was measured directly, and a graph of breakdown field

to work function was found to be linear with a slight scatter.

In a paper (34) in 1936, Ahearn described experiments using a coaxial system which gave high fields with comparatively low voltages ($<30\text{KV}$). He found that the degree of thoriation and temperature of the cathode had no appreciable effect on the breakdown voltage. To determine if the breakdown could be induced by the field alone, the voltage was applied with the filament as anode, and no breakdown was obtained at cathode fields greater than normal. This seemed to show that the emission of current was an important feature. Ahearn found that breakdown could be suppressed by having a high resistance in series with the anode - breakdown occurred with 1.0×10^5 ohms in series but not with 1.0×10^8 ohms. One section of the anode was shielded and the other part 'conditioned' by breakdowns. The shielding was then reversed, and it was found that the breakdown voltage was actually greater for the previously shielded section, which seemed to rule out the anode as a determining factor. By using a movable concentric glass cylinder it was found that exposed glass had a considerable bearing on the breakdown voltage. At breakdown the current would increase from less than 10^{-6} amperes to greater than 10^{-3} amperes and the cathode breakdown gradient would be from 100KV/mm - 200KV/mm . Ahearn stated that the evidence from these experiments indicated that the breakdown is determined primarily by conditions at the cathode, and suggested that the experiments of Bennett which showed an anode effect were confused due to exposed glass. He then proposed the following mechanism for

breakdown. Prior to breakdown, field currents flow from a few of the surface projections where the local field and the mechanical force are greatest. There will be local resistive heating which will depend upon the size and geometry of these projections and their thermal contact with the body of the cathode. As the field is increased, a rupture occurs at that projection where conditions of mechanical force, resistive heating and tensile strength are most favourable. When the rupture occurs, a large breakdown current flows due to the greatly enhanced local field strength, and subsequently at lower macroscopic gradients much larger field currents are obtained.

Moore (35), in 1936, described impulse breakdown studies using a spherical anode and a mercury cathode. He obtained cathode breakdown gradient - work function curves similar to those of Quarles (33), (i.e. linear and with the same slope) and extended them to higher cathode field strengths (60KV/mm.). It was found that the breakdown potentials were consistently higher (about 4 or 5% on average) if the wave front of the impulse was made steeper, and it is mentioned that Snoddy in some unpublished work found a similar increase for solid cathodes. This was accounted for by the finite time necessary to initiate a vacuum discharge. The impulse wave fronts were of the order 10^{-7} second.

Mason (36), in 1937, described vacuum breakdown experiments at up to 50KV between a copper disc anode and a tungsten filament cathode in the form of a semicircle, the plane of which was perpendicular to the copper disc. He found that breakdown

took place at approximately the same value of cathode gradient (60KV/mm.) for different spacings and with different thermionic emission currents. He considered that if positive ions were of importance in the breakdown process, a mechanism such as $\gamma\delta \geq 1$ would hold at breakdown where

γ is the number of positive ions produced per electron striking the anode,

δ is the number of electrons produced per positive ion striking the cathode.

Mason considered that if such a relationship was valid, an increase in the thermionic emission should decrease the breakdown voltage. He stated that as this was not so, positive ions did not play a part in the breakdown process. The experiments do not, however, seem to justify such a conclusive statement. Vacuum breakdown is a very local phenomenon and a relationship such as $\gamma\delta \geq 1$ is required only to hold locally. Increasing the electron yield from the cathode generally by thermionic emission might quite conceivably have little effect locally, and the increase in temperature might even smooth a local projection or drive off an impurity, so giving a higher breakdown voltage. It is of interest to note that Mason did actually find a slightly higher breakdown voltage with the cathode hot. Some impulse breakdown experiments on aluminium electrodes with a wave which rose to a 60KV crest in 1.5 micro seconds gave much higher breakdown figures than with direct voltage. It was suggested that this was due to the time lag caused by the finite time required for the passage of vapour across the gap.

In 1944, Jin Imachi (37), described experiments which showed that breakdown was more affected by the material of the anode than that of the cathode. Any conducting or nonconducting projection on the surface of the electrodes, particularly on the anode, caused breakdown at a lower voltage. The breakdown voltage was lowered when ions, but not electrons, were made to enter the gap from outside. Hence he deduced that the vacuum breakdown was mainly due to positive ions produced at the anode by electron impact.

Hashimoto (38) published a paper in 1947 giving results obtained with a point to plane electrode system which was tested with impulse voltages up to 100KV, and at a pressure of 10^{-5} mm. of mercury. The breakdown voltages obtained were approximately the same whether the electrodes were nickel point and nickel plate or molybdenum point and brass plate. A much lower breakdown voltage was obtained with the point negative than with it positive. The geometry of the point is not given. The discharge voltage appeared to depend on the characteristics of the negative electrode. Hashimoto suggested that breakdown was caused by bombardment of the anode by field emission electrons which melt the metal or ionise the gas molecules adsorbed on the surface. Pictures were given showing the figures produced on the plate surface, but they are rather intricate and difficult to analyse.

One of the major works on high vacuum breakdown is that of Trump and van de Graaf (39) in 1947. They describe direct voltage breakdown studies between sphere and disc electrodes in

high vacuum and at voltages from 50 to 700 KV. These experiments demonstrated the inadequacy of the field emission theory to account for the higher voltage breakdown. Trump and van de Graaf considered the fact well established that voltage breakdown between electrodes in high vacuum at high gradients, but relatively low voltages is initiated by high field emission. This emission increases exponentially with cathode gradient, and results in local temperature increases and enhanced secondary effects, which lead to instability. They produced figures which showed quite definitely that this field emission could not account for breakdown at higher voltages, where the gradient is very much lower. Their figures showed that the cathode gradient at breakdown (with voltages higher than approximately 50 KV) decreases as voltage increases. This is shown on their curve of breakdown voltage and gradient to gap spacing (graph 2). They reiterated the breakdown mechanism proposed by van Atta, van de Graaf and Barton in 1933. (Page 10). Trump and van de Graaf described experiments to measure coefficients A and B under conditions which were not, however, quite as stringent as in an actual gap. Although the particle velocities were commensurate with the high vacuum gap condition, the field at the secondary emitting surface was not. Bearing this in mind it appeared possible that such a mechanism could play a part in vacuum breakdown at the higher voltages. Experiments were being considered to measure coefficient B under actual gap conditions and also the photon process mechanisms C and D.

In 1948, McKibben and Beauchamp (40), described experiments connected with a 12 Mev. accelerator tube. They considered that photons need not be considered in any proposed breakdown mechanism since it was noted that sparks took place between a small spot on the cathode and another on the anode. They mentioned that Haynes (41), had shown that partially ionised vapour jets came from a mercury electrode whether it was positive or negative, and that the sign of the ions was the same as the electrode. McKibben and Beauchamp proposed a mechanism of a similar nature to that of Van Atta et al (28), but excluding the photon process and including a negative ion process. If

1 electron on the anode produces A positive ions,
1 positive ion on the cathode produces B electrons,
1 positive ion on the cathode produces C negative ions,
1 negative ion on the anode produces D positive ions,
then breakdown occurs if $AB + CD \geq 1$.

They observed that jets came from the anode and were deposited as fine droplets fused on to the cathode, and it seemed likely to them that for sparking between most metals the AB mechanism was dominant. It had also been observed that the presence of almost any gas up to approximately 50 per cent of the pressure at which continuous discharge took place, increased the sparking potential. They suggested that the electrons might be scattered so that local heating of a sensitive area on the anode did not take place so readily.

They mentioned the facts that Rother (42), who used well outgassed tantalum electrodes, was able to observe field emission

currents up to gradients of 850KV/mm. and 620KV/mm. for gaps of .005mm. and .02mm. respectively. Also, Trump et al (39), found that the approximate breakdown gradients for gaps of 0.1mm. and 70mm. were respectively 300KV/mm. and 10KV/mm. McKibben and Beauchamp found that figures such as these could not be obtained with parallel plane electrodes which had not been extensively conditioned. With steel electrodes and a gap of 9mm. the first spark occurred in the range 60-100KV. If the gap voltage was maintained sufficiently high for occasional sparks to occur, it would be found that after a few hours the gap would withstand (approximately 1 spark per hour) 110-160KV. The first sparks of the conditioning process released gas from the electrodes, but as the conditioning continued the bursts of gas were seen to be smaller. It was then that a spark was liable to damage the surface, and they suggested that the released gas scattered the electron beam, so that the spark did not become too concentrated.

The spark frequently damaged the electrodes if the gap was less than about 0.25 inch. The gradient and thus the field emission current were higher at such short gaps, and it was also suggested that space charge and scattering had less chance of spreading the discharge over an area large enough to prevent damage.

Of the materials tested, gold had the lowest breakdown voltage and copper was almost as bad. Tantalum and molybdenum did not seem to be as good as steel. Nickel and stainless steel seemed to be on a par with steel, or perhaps superior, and magnesium electrodes were as hard to condition as the others

and were easily damaged. Aluminium and dural had about the same breakdown voltage as steel, and were unique in that they conditioned to their top voltage in a few minutes when, however, they were easily damaged by sparks. This listing does not agree with that of Anderson for gaps of one millimetre. It would seem from the breakdown figures given that the conditioning was incomplete - this being particularly evident at the smaller gap spacings. The results of McKibben and Beauchamp are given on graph 3.

In 1951, Gleichauf described experiments on breakdown over insulators, and mentions that for copper electrodes and pyrex glass the arc-like discharge extinguished at a current of approximately 1 ampere. No stable discharge was observed, if the resistance in series with the test sample was increased to keep the maximum current below one ampere. Apparently the discharge takes place with a current of one ampere but lasts for a short time (10^{-5} to 5×10^{-5} second). Increasing the capacitance of the gap increased the time of discharge, and indicated that the breakdown current was due to the discharging of the capacitance of the test sample. Copper electrodes were tested without the insulator at a gap of a few millimetres, and the extinguishing current was found to be similar (0.7 to 1.5 amp) to that when an insulator bridged the gap.

In a later paper (44), Gleichauf mentioned that if a thin layer of glass was fused to the cathode of a vacuum gap, the breakdown voltage was lowered by about 25%, whereas a fusing on the anode gave no change.

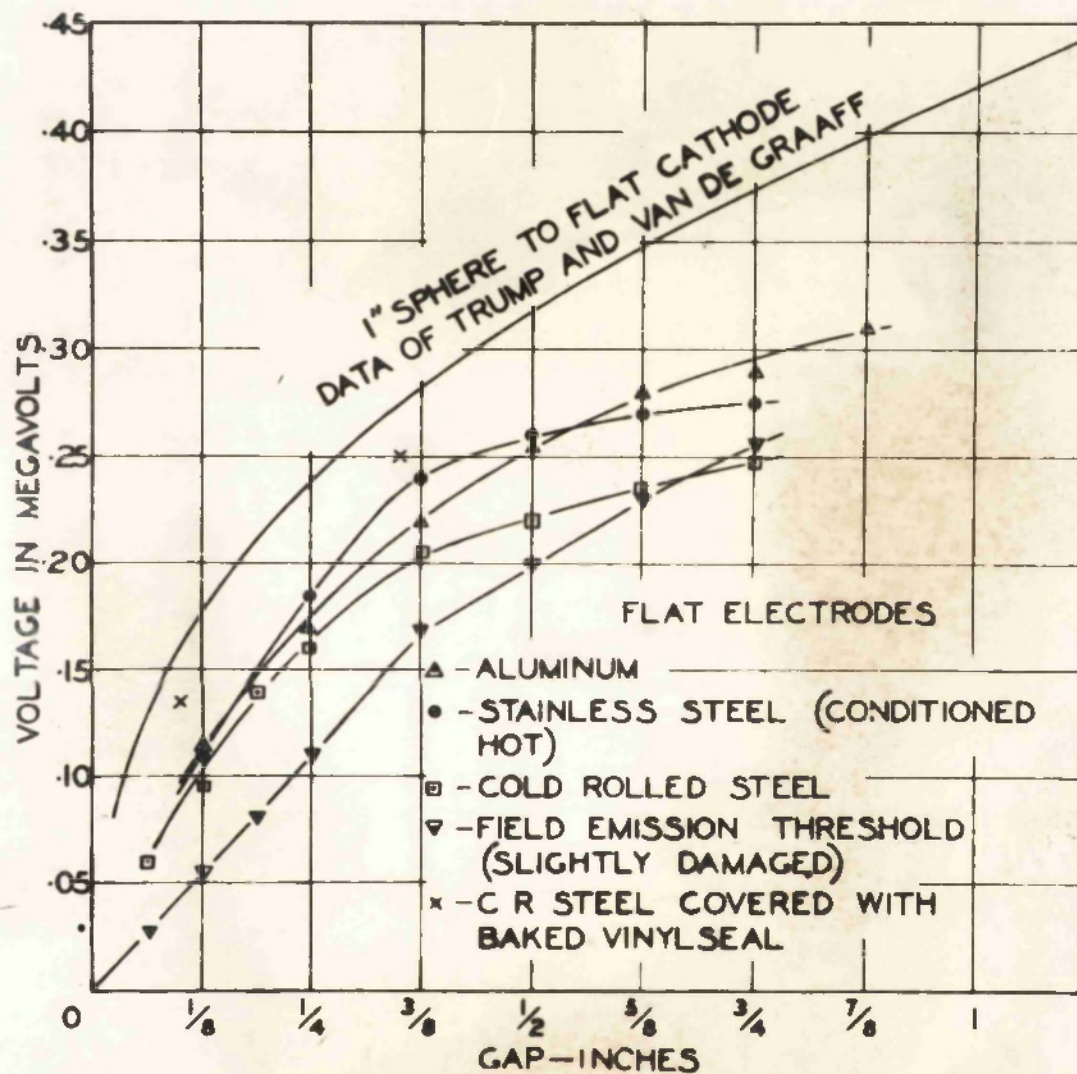


Figure-5. Breakdown voltages for various electrodes at about 1 spark per 5-minute interval.

Graph 3 (Ref 40)

Heard and Lauer (45), in 1952, described a study of the transfer of anode metal which occurs at a voltage below that required for sparking. They used Cu^{64} as a radioactive tracer. These experiments were with regard to that part of the breakdown mechanism proposed by Trump and van de Graaf which involved the transfer of ions from the anode to the cathode. Previous experiments (39, 46), had shown that a positive ion current flowed from the anode to the cathode in the presence of a high voltage, but there remained the possibility that this was due to the ionisation of a film of gas on the anode surface. Heard and Lauer showed that actual anode metal crossed the gap, and the amount of metal transferred indicated that it either crossed uncharged, or as a small aggregate of atoms, a few of which were ionised. There were indications that spacing and gradient, rather than the total voltage, were the controlling factors in the amount transferred.

The current between the electrodes was found to be composed of a steady and randomly fluctuating component. This latter component was found to be independent of pressure, but dependent on the total gap voltage and the electrode spacing. These fluctuations would usually decrease with time and could not be used to foretell breakdown. The gap current fluctuation with time was not understood. The electrodes used in these experiments were not outgassed.

In the same year (1952) Cranberg (47), presented a paper in which he proposed that high vacuum breakdown is initiated by a traversal of the gap by a 'clump' of material which had been

adhering loosely to an electrode. He gave a summary of the literature which supported this conclusion for uniform or near uniform, field conditions over a range of voltages from 20 KV. to 7 MV. (graph 4). The proposed hypothesis and supporting data were as follows. Loosely adhering material (termed a 'clump' by Cranberg) can be detached from an electrode by electrostatic repulsion. The initiation of breakdown is due to this 'clump' crossing the gap and striking the other electrode, where, it can be shown, local temperatures are produced which are in excess of any known boiling points. It was assumed that production of such a condition would lead very quickly to the development of the full breakdown, but details of subsequent events were not given in the paper.

Assume breakdown will occur when the energy W per unit area delivered to the target electrode exceeds a value C' , a constant characteristic of a given pair of electrodes. This quantity W is the product of the gap voltage V and the charge density on the clump. The latter is proportional to the field strength E at the electrode of origin, so that the breakdown criterion becomes simply

$$VE \cong C,$$

where C is a product of C' , some numeral factors, and possibly a field intensifying factor due to microscopic field inhomogeneities in the neighbourhood of the clump during detachment from its parent electrode.

For a uniform field gap, $E = \frac{V}{d}$ and the voltage which the gap can sustain is proportional to the square root of the gap length

for a given pair of electrodes. That is, $V \geq (Cd.)^{\frac{1}{2}}$ is the breakdown criterion.

Cranberg's summary of pertinent evidence from the literature is given in the form of a double log plot on graph 4. The curves are seen to be good straight lines, in general with slope one half, and typical values for C are about $3MV^2$ per foot. This quantity C suffices as a figure for the vacuum insulating properties of the gap, and provides a basis for comparison of data under different conditions of gap and voltage.

Cranberg considered that in the case of non-uniform field geometry, the relevant data (table 1) was not sufficient for definite conclusions to be drawn. The figures seemed consistent equally with interpretation in terms of cathode gradient, or in terms of voltage-field product. The values of C were in the same range as those for uniform field conditions, which seemed to indicate that it is the product of the total voltage and cathode gradient which controls the beginning of the discharge. Other qualitative measurements indicated that breakdown with a high gradient at the anode is of the same order as with a high gradient at the cathode, other things being equal. Cranberg suggested that the cathode gradient determines the breakdown voltage unless the gradient at the anode is considerably greater than that at the cathode. It was stated that certain qualitative aspects appeared to support this hypothesis.

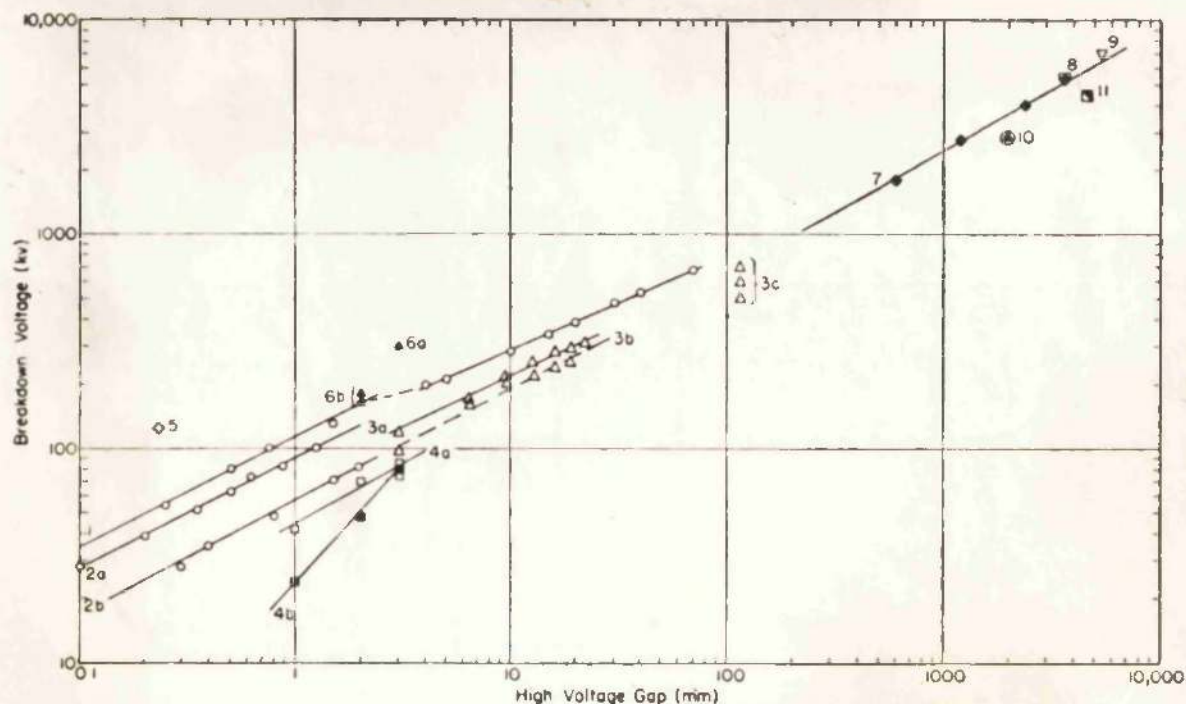


Fig. 1. Plot of data from the literature of breakdown voltage vs distance from highest to lowest potential electrode, for uniform-field and near-uniform-field geometry. Numbers on curves indicate sources as listed below.

- (1) Trump and Van de Graaff, (see reference 8) 1-inch sphere steel anode, 2-inch steel disk, outgassed with glow discharge.
- (2) Wm. Parkins, "Vacuum Sparking Potentials under Surge Conditions," MDDC 858, 18 February, 1946. Voltage applied in pulses of 3×10^{-7} sec rise time. (a) Tungsten hemispheres 2-inch diameter, out-gassed by spark discharge. (b) Copper hemispheres 2-inch diameter, out-gassed by spark discharge.
- (3) J. L. McKibben and R. K. Beauchamp, "Insulation-Flashover Tests in Vacuum and Pressure," AECD 2039. (a) Flat aluminum. (b) Flat cold-rolled steel. (c) Van de Graaff test-section 4 1/4 inches long, aluminum rings sandwiched between Mykroy rings, steel anode plate, negative end open to vacuum system in simulation of operation as beam tube, results on three test-sections.
- (4) Gleichauf (see reference 12). (a) Kovar cathode, 18-8 st. steel anode, flat with rounded ends. (b) Copper, flat, with rounded ends (hole in center of anode).
- (5) R. J. Piersol, British Assoc. Advancement of Science, Report 359 (1924). Molybdenum spheres after heating to 1400°C .
- (6) J. L. Hayden, Am. Inst. Elec. Engrs. J. 41, 852 (1922). (a) Molybdenum spheres 1-cm diameter out-gassed to red heat, polished. (b) Molybdenum spheres 1-cm diameter.
- (7) Los Alamos big Van de Graaff, polished aluminum electrodes.
- (8) Robinson *et al.*, Phys. Rev. (to be published).
- (9) J. G. Trump (private communication on performance of new 12-Mev Van de Graaff machine, polished aluminum electrodes.
- (10) Los Alamos small Van de Graaff machine (not limited by tube sparking), steel electrodes.
- (11) Wisconsin Van de Graaff machine (not limited by tube sparking), steel electrodes.

Graph 4 (Ref. 47)

INITIATION OF ELECTRICAL BREAKDOWN IN VACUUM

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TABLE I.

Reference	Geometry	Anode	Cathode	Electrode treatment	$V(10^6 \text{ volts})$	$E_{\text{cathode}} 10^4 \text{ volts/ft}$	$VE_{\text{cathode}} 10^{11} \text{ volts}^2/\text{ft}$
C. C. Chambers J. Franklin Inst. 218, 463 (1934)	Cylindrical	Nickel	0.5 Mil tungsten	Wire heated to 2800°K for 30 min.	$0.011 \pm 10\%$	78	0.86
			1.6 Mil tungsten	Cylinder heated to dull red heat for 5 min.	$0.023 \pm 10\%$	60	1.30
A. J. Ahearn, reference 6 and Phys. Rev. 44, 277 (1933)	Cylindrical	2 cm diam nickel	Thoriated W 1.0 Mil		0.017	60	1.0
			Thoriated W 1.0 Mil		0.024	78	1.9
			Pure W 0.6 Mil		0.015	84	1.3
			Pure W 1 Mil		0.023	81	1.9
R. C. Mason, Phys. Rev. 52, 126 (1937)	Line-plane	2"-diam. Cu disk	28 mil tungsten wire in 1"-diameter semi-circle	Everything baked out to 500°C	0.035	18	0.63
K. Hashimoto, reference 15	Point-plane	Nickel	Nickel point	Conditioned by sparking	0.030 0.090		for 1 mm separation
		Plane Nickel Point	Nickel plane				

Table 1 (Ref. 47)

The conditioning process, which requires the gap to be maintained at a high voltage with, or without, sparking, can be explained by considering that the most loosely adhering material is detached from its parent electrode, accelerated across the gap, and firmly embedded on the opposite electrode. The fact that the gap may breakdown after withstanding the applied voltage for minutes or hours seemed consistent with a hypothesis having the discharge initiated by a single event. The difficulty of reproducing the breakdown voltage is also in agreement with the general character of the mechanism.

In 1953, Leader (48) described experiments on the breakdown between spheres, and between sphere and point electrodes. He conditioned his electrodes by high voltage breakdowns, until a stable end point was reached, and the highest value attained was taken as the breakdown voltage. His results using direct voltages were erratic. Individual values of breakdown voltage were sometimes 25% above, or below, the average for a large number of tests. As the voltage was increased, the pre-breakdown current increased, and it was difficult to determine the breakdown point.

Impulse voltages (1.5/70 microsec. waveshape) up to 55KV. were applied between electrodes and the values of breakdown voltage obtained were reproducible to within $\pm 7\%$. Leader does not define the value he took as the breakdown voltage, or describe his test procedure, but it is probable that the impulse voltage was raised incrementally until a discharge occurred. The peak value of the impulse wave would be taken as the breakdown voltage.

The point at which sparking commenced and ceased was well defined, and the sparks were clearly visible.

The results obtained by Leader for various forms of steel electrodes are shown on graph 5. He based his reasons for the higher breakdown voltage with the sharper electrodes, on the theories of Trump and van de Graaf (39). He suggested that the small area of a point electrode might cause photons, positive ions, and to a lesser extent electrons, from the opposite electrode, to pass the extremity of the point without striking. A voltage higher than that which would cause breakdown between two spheres would be necessary for the process to become cumulative.

Oscillograms of the impulse breakdown of sphere gaps showed that the breakdown occurs in approximately 0.12 microseconds, which is in agreement with the results of Gossling (23) and Snoddy (20). The oscillograms showed that the discharge extinguished at currents of about 0.25 amperes. This is in fair agreement with Gleichauf's values of 0.7 to 1.5 amperes for copper electrodes. A complete breakdown would not occur if the limiting resistor was made large enough to prevent a current of 0.25 amperes from flowing. Leader found that under such conditions of high limiting resistor, the current oscillogram would take the form of a relaxation oscillation which represented the repeated discharge of the gap capacitance. He suggested that the difficulties experienced by previous experimenters who used d.c. could be due to their series resistance being too high - the resulting oscillation would give an integrated reading on a galvanometer.

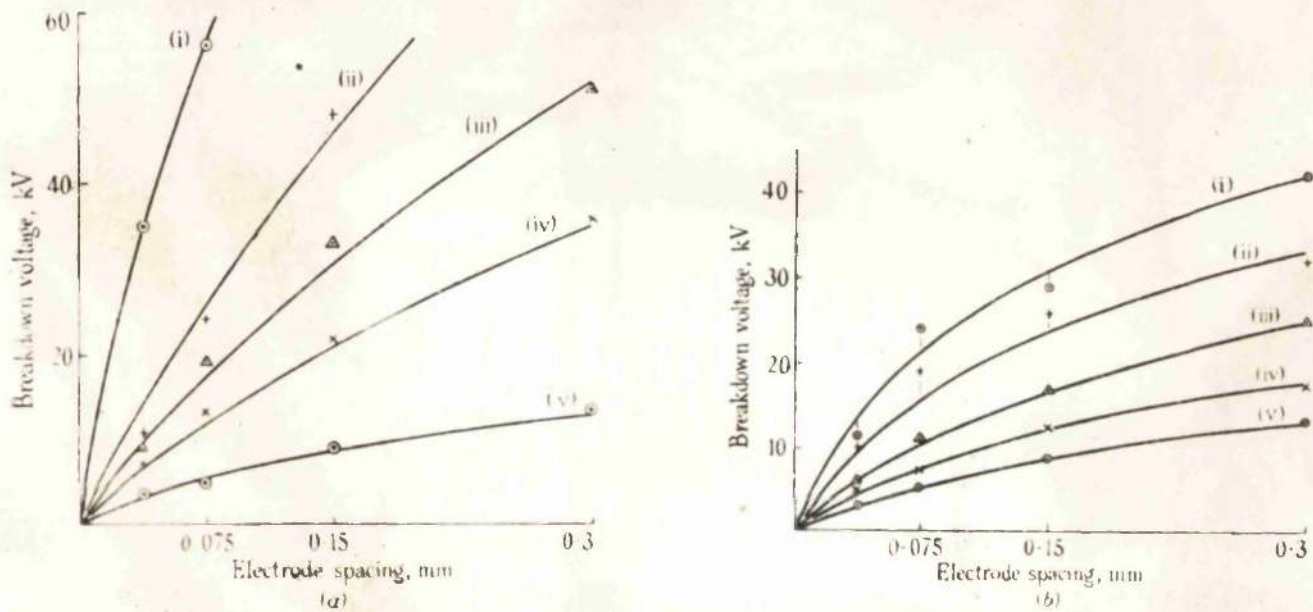


Fig. 2.—Variation of breakdown voltage with electrode spacing and construction.

- (i) Sphere and finely tapered needle.
- (ii) Sphere and 0.015-in wire.
- (iii) Sphere and 0.032-in wire.
- (iv) Sphere and 0.062-in wire.
- (v) Two spheres.
- (a) Wire positive
- (b) Wire negative

Graph 5 (Ref. 48)

In February 1953, Dyke and Trolan (4) described field emission studies on single crystal, tungsten 'needles', the geometries of which were determined by electron microscopy. The experiments were carried out in a vacuum of the order of 10^{-12} mm.Hg. using a needle cathode and plate anode, both of which were well outgassed. The voltage was applied in micro-second pulses. The results verified the theoretical wave mechanics equation for field emission, with indications that the field emission was being space charge limited at the higher current densities.

Table II shows the current densities just before breakdown (\bar{J}_x) and the voltage at breakdown (V max.)

TABLE <u>II</u>				
Emitter No.	\bar{J}_x amp/cm ²	V max.KV.	F max.KV/cm	V max x F max
X 89	2×10^7	6.9	8,820	$60.9 \times 10^3 \text{ KV}^2/\text{cm.}$
X 81	3×10^7	6.9	10,100	$69.6 \times 10^3 \text{ KV}^2/\text{cm.}$
N 10	2×10^8	32.1	12,800	$410.0 \times 10^3 \text{ KV}^2/\text{cm.}$
Q 7	6×10^7	4.75	9,250	$44.0 \times 10^3 \text{ KV}^2/\text{cm.}$

Dyke and Trolan suggested that the maximum current densities were in sufficient agreement to indicate that the current density was the most important variable in a determination of the breakdown point. If, however, the maximum cathode gradient at breakdown is calculated from their results, the figures shown in column four are obtained. They seem to be in much closer agreement than the current densities. The product of the applied voltage and the maximum cathode gradient (see Cranberg (47)) is given in column five. It was suggested that the

breakdown results from increased emitter temperature due to a current density dependent mechanism accompanying the emission process. Possible mechanisms which could have produced the required heating are resistive heating and the Nottingham mechanism (49). A solution for the adiabatic case applied to the emitters (the voltage was applied in single micro second pulses) showed resistive heating giving excessive emitter temperatures when $J = 10^7$ amp./cm.².

It was seen from oscillograms that at formation of the arc the current increased by two orders of magnitude in 5×10^{-8} sec.

The authors considered that in view of the pulse nature of the voltage and transit time considerations, it was unlikely that the breakdown was initiated by ions or clusters liberated at the anode.

In the September of the same year, Dyke, Trolan, Martin and Barbour (50, 51), published further information on the breakdown studies just described (4). This showed conclusively that the vacuum arc in their experiments was initiated at a critical value of the field current density (about 10^8 amperes/cm.²) They were able to compute the current densities necessary to give (by resistive heating) a temperature of 3000°K on the cathode in the time of duration of the applied voltage. Table III shows how well the experimental(J_x) and calculated (J_r) current densities corresponded. Dyke et al. found that they could predict that breakdown was about to occur by noting a 'tilt' in the current pulse. That is, the emission current increased noticeably over the short period(usually micro second)

for which the voltage was applied. This was due to the high temperatures developed at the emitting point.

TABLE III

Emitter.	Jx. <i>amp/cm²</i>	Jr. <i>amp/cm²</i>	V max.(KV).	Pulse Duration ⁻⁶ (10 second).
0 38	6 x 10 ⁷	7 x 10 ⁷	9.2	1
X 62	4 x 10 ⁷	2.4 x 10 ⁷	8.8	0.5
X 62A	3 x 10 ⁷	2.5 x 10 ⁷	60.1	1
Q 1	4 x 10 ⁷	7.1 x 10 ⁷	4.9	1
Q 29	7 x 10 ⁷	7.4 x 10 ⁷	14.2	1
O 54	1 x 10 ⁸	2.7 x 10 ⁸	16.1	1
2 x 4	5 x 10 ⁷	5.8 x 10 ⁷	13.3	1

The following mechanisms have been suggested to account for high vacuum breakdown. Some (a & b) were proposed to explain breakdown at low voltages and high surface gradients, and others (c & d) to explain breakdown at high voltages and comparatively low surface gradients. Cranberg's theory (e), it was suggested, is general.

(a) (23) The discharge is due to large field emission currents from points produced by some form of surface rupture under the influence of applied fields.

(34, 48) Prior to breakdown, field currents flow from the surface projections where the local field and the mechanical force are greatest. Depending on the size and geometry of these projections and their thermal contact with the body of the cathode, there is local resistive heating. As the field is increased, a rupture occurs at that projection where conditions of mechanical force, resistive heating, and tensile strength are most favourable. Breakdown occurs.

(b) (31) A certain number of positive ions are formed for each electron striking the anode. These ions are accelerated towards and bombard the cathode. When the potential and the number of ions are both large enough, a rupture of the cathode occurs.

(c) (28, 39). Breakdown occurs when $AC+BD \geq 1$ where the co-efficients A,B,C and D are as specified on page 10

(d) (40). Breakdown occurs when $AB+CD \geq 1$ where the coefficient A,B,C and D are as specified on page 22

(e) (47). Cranberg's 'Clump' Theory (page 26). Breakdown occurs when $VE \geq C$, which gives for uniform fields $V \geq (Cd.)^{\frac{1}{2}}$.

If mechanism (a) alone determined the breakdown point, the anode condition would have no effect on the breakdown voltage. Of the experimenters who investigated the effect of the anode, only Ahearn (34), and Gleichauf (44), found it had no effect, while the work of Bennett (19, 21), Beams (22), Chambers (31), Anderson (32), Imachi (37) and Heard et al (45), indicated that it had. The experiments of Anderson (32) and Trump et al (39) which showed the total voltage effect, indicate conclusively that this process can not alone account for the breakdown at high voltages ($> 50KV$).

The mechanisms (b), (c), (d), and (e) are consistent with the anode condition affecting the breakdown voltage and with the phenomenon of anode metal transfer prior to breakdown. Measurements in recent years (39, 46, 52) on the coefficients involved in (c) have indicated that they are not large enough to account for breakdown. Measurements under breakdown conditions have not, as far as is known, been made on the negative ion emission coefficients involved in (d).

The curves given by Cranberg (figure 4) give strong support to his theory of breakdown under uniform field conditions, particularly at voltages above about 50KV. Under non uniform field conditions the evidence is not conclusive.

The experiments of Chambers (31), which would appear to be the classic breakdown study on coaxial systems, do not positively confirm this theory, although the anode condition definitely affects the value of the breakdown voltage. The mechanism

proposed by Chambers (page 14), which is a combination of (a) and (b), seems a more likely cause of breakdown. The experiments of Dyke and Trolan showed that the emission of current from a point could alone cause breakdown by resistive heating, but the nature of their experiments (microsecond voltage pulses) was such as to eliminate the other possible causes which would depend on the anode. As they state - "In view of the required rate of ion delivery, the excellence of the vacuum, and transit time considerations, it is unlikely that the present breakdown was initiated by ions or clusters liberated at the anode."

From this survey it seems probable that the following mechanism causes breakdown at comparatively low potentials (≤ 50 KV.) and high surface gradients if the positive ion transit time is short compared with the time of duration of the voltage. As the gap voltage is increased, electrons are emitted from a projection, and there is local heating due to the high current density. These electrons cross the gap, strike the anode, and produce by secondary emission, ions which are accelerated towards the cathode and bombard the projection, giving further heating. Breakdown thus occurs at a lower current density and hence a lower surface gradient at the cathode, than that necessary in the experiments of Dyke and Trolan. (Their cathode breakdown gradient was 822 - 1,280 KV/mm.) The extent to which the spark potential depends on the current density will be determined by the number of positive ions produced by the electron stream. This will be greatly influenced by the condition of the anode surface. (Chambers found no breakdown at a gradient of 600 KV/mm. on his 'heat smoothed' cathode after outgassing his

anode - this figure is just below the lowest breakdown gradient obtained from Dyke and Trolan's figures.)

Consider now the two experimenters who found no anode effect. Ahearn's method of 'conditioning' the anode was by causing a few breakdowns to occur (page 17). It is possible that only a small fraction of the anode surface would be outgassed in this way, whereas the cathode would probably be conditioned by removal of projections. The fact that a slightly higher breakdown voltage was obtained when the previously shielded part of the anode was rotated into position, bears out this supposition. Gleichauf found that fusing a film of glass on the anode did not affect his breakdown voltage. This is not incompatible with the proposed mechanism if the emission of positive ions is largely determined by the adsorbed gas (as is supported by outgassing experiments) rather than by the actual anode material.

2. Equipment.

2.1. The Vacuum System.

The vacuum system was of metal construction apart from the pyrex bell jar (fig. 1). Vacuum tight jointing was effected at the points marked by Gaco 'O' rings, and at the bell jar base by a neoprene 'L' gasket. The heavy, metal base on which the bell jar sat had four Edwards bushings fitted (two rated 15 KV., 100 amperes and two rated 7 KV., 15 amperes), and a sealed screw in the top of the jar carried the high voltage supply into the vacuum chamber. Motion was transmitted through the vacuum wall by means of simply constructed Wilson seals which are shown on figure 2.

The pressure in the system was measured by a thermocouple guage and an ionisation guage incorporated as shown on figure 1. The guage ranges were respectively 1 mm. of Hg. to 10^{-3} mm. of Hg. and 10^{-3} mm. of Hg. to 2×10^{-7} mm. of Hg.

2.2. Provisions for Conditioning.

Facilities were required for

- (a) running a discharge between the electrodes in a hydrogen atmosphere and
- (b) heating the electrodes strongly in a high vacuum.

The hydrogen discharge was provided for by a needle, leak valve (B) in the system as shown in figure 1. When it was necessary to fill the bell jar with hydrogen, the vacuum system was pumped to the minimum rotary pump pressure (about 10^{-3} mm. of Hg.), the valve A closed, and hydrogen injected at valve B. Facilities for induction heating the electrodes were provided

by having work coil C (fig. 1) connected by heavy, braided copper to the larger bushings in the bell jar base. The support for the coil was racked at its lower end, and could be driven up, or down, by a pinion which was rotated by a spindle through a Wilson seal. In this way the coil could be removed from the vicinity of the gap after heating.

Consideration of the induction heating problem showed that, with the oscillator components available and with fixed matching, the highest attainable temperature for steel electrodes was the Curie point (approximately 800°C - a bright red heat). In the case of other electrode materials it was proposed to use magnetic cores. A circuit diagram of the 0.5KW. induction heating equipment which was designed is shown on figure 3.

With the electrodes at a red heat it was necessary to have the supports water cooled, or of such a form as to prevent excessive heat flow to other parts of the equipment. Thermally insulating supports were adopted, since the power then required to heat the electrodes was much smaller. The supports were made of thin walled steel tube ($< 0.008"$) which gave the required low rate of heat flow.

2. 3. The Electrode System.

The geometry of the disc type electrodes used is shown on figure 4. This proved a suitable shape for high vacuum breakdown studies, since for all practical purposes the field at the centre was uniform, although the area to be conditioned was small. No edge effects were experienced. The electrode metals were analysed and the following figures obtained.

Steel - Fe. 99.518%, Mn. 0.380%, C. 0.052%,

Copper- Cu. 99.5%, impurities unknown.

Aluminium - Al. 99.64%, Si. 0.23%, Fe. 0.1%, Cu. 0.03%,
Mg. 0%

The bottom electrode could be moved vertically by a micrometer which was operated by a drive through a Wilson seal. When the electrodes touched they completed a temporary electrical circuit comprised of a 4 volt battery in series with a bulb. (Rother (42) found that zeroing his gap in this way did not adversely affect the electrode surfaces). To set the gap, the bottom electrode was raised until it touched the top electrode and the micrometer reading noted. The bottom electrode was then lowered and the micrometer set to give the desired gap. The micrometer could be read to within ± 0.0001 ".

3. A.C. Breakdown Tests.

3. 1. A.C. Equipment.

The high voltage circuit is shown in figure 5. The polarity indicator (figure 6) is a modified form of that given in reference 53 with the resistors (R_p) increased to make it more sensitive, and the relay (L_2) included to open the primary circuit of the high tension transformer when the gap broke down. As was expected, it was discovered that there was no polarity effect and the main use of the indicator was in de-energising the circuit at breakdown. The current necessary to trip the polarity indicator was determined by the values of R_1 and R_2 and could be as small as 800 microamperes. The cathode-ray oscillograph was used for the measurement of pre breakdown current.

The peak voltmeter, which used negatively biassed triodes to prevent circulating current, is shown on figure 7. The voltmeter was checked against another which was accurate to within 0.2%. The other instrument was developed in this department by Mr. J. Mathews. The voltage figures corresponded to within 0.75%, which indicated that the peak voltmeter used in the present work was accurate to within $\pm 1\%$. Often when it was not suitable to watch the milliammeter constantly, the reading on the primary voltmeter would be taken after breakdown. A calibration curve of milliammeter to primary voltmeter reading showed a maximum deviation of 3% from the mean, with the vast majority of readings well within this limit. A few check readings on the milliammeter would be taken in each

test in which the primary voltmeter readings were being used as the voltage indication. The peak voltage is given by the relation $\hat{V} = \frac{1}{2fC}$, and it is necessary to know accurately the supply frequency. This was measured by putting the supply voltage across the X plates of a Cathode-ray oscillograph, and a signal from the contacts of variable frequency tuning fork across the Y plates. The fork frequency was adjusted to give a stationary picture on the screen, and the supply frequency was thus known to the accuracy of the fork frequency, namely $\pm 0.2\%$.

Gas gaps were placed across the peak voltmeter and polarity indicator for surge protection at breakdown.

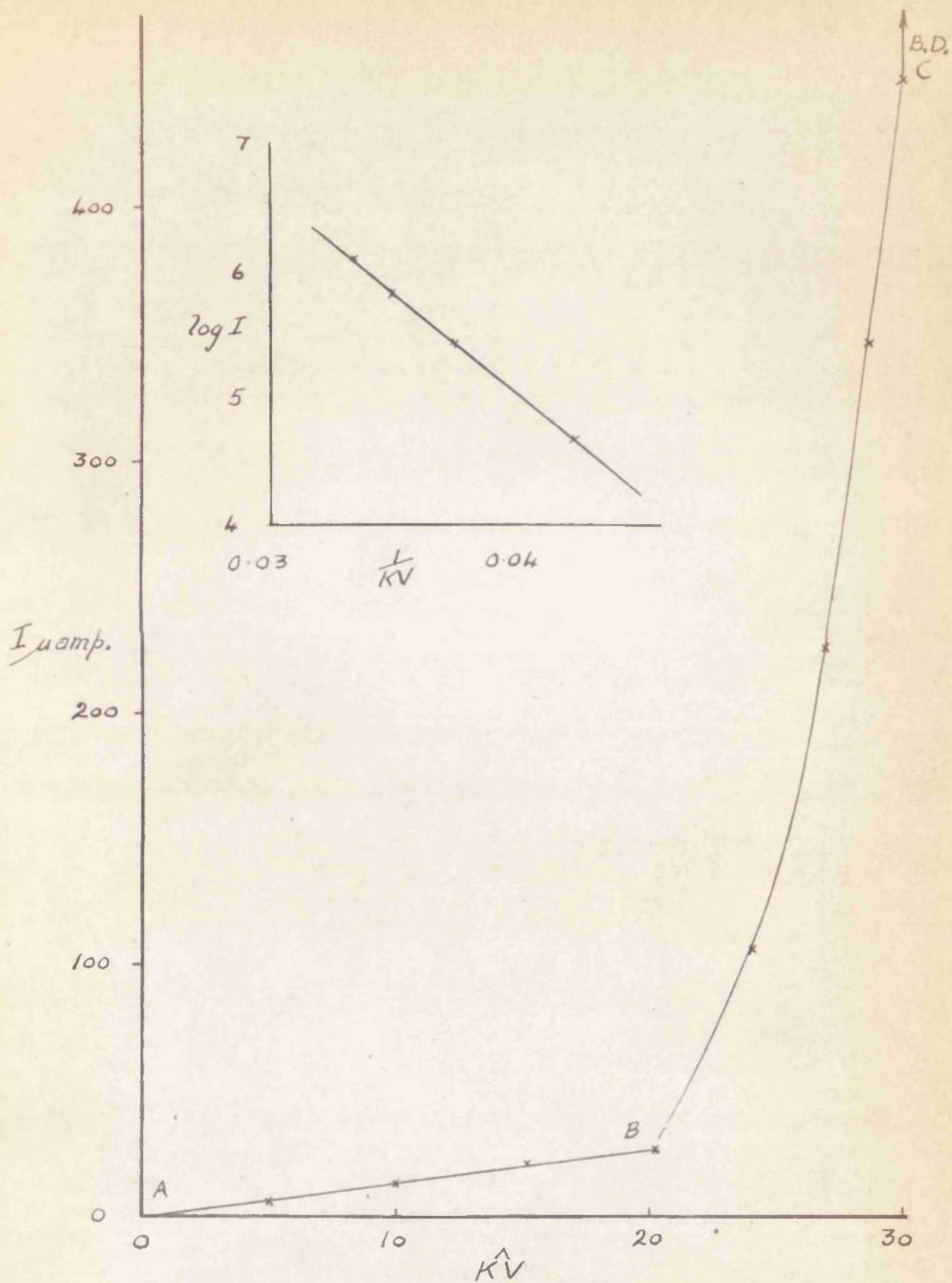
3. 2. The Breakdown between Steel Electrodes.

3. 2. 1. The Current-Voltage Characteristic of a Vacuum Gap.

When an alternating voltage is applied across a vacuum gap, the current which flows will, in general, have a wave form as shown on plate 1. A field emission current, which is in phase with the voltage across the gap, is superimposed on the capacitance current. The value of this emission current depends on the metal, degree of adsorption, and to a greater extent, on the roughness of the cathode.

Graph 6 shows a curve of peak current to applied voltage for unconditioned steel electrodes which had been roughened very considerably by many breakdowns. Portion A B represents the capacitance current peak and B C the field emission current peak. At some point (C), a discontinuity occurs and the current increases to a much larger value which is determined by the circuit conditions. This point C is defined as the breakdown point. Section B C of the curve is governed largely by the empirical field emission law (p.1), as is shown by the graph $\log I - \frac{1}{KV}$ on the same sheet. The emission current is negligible compared with the capacitance current if the cathode surface is smooth, and there is no apparent irregularity on the sine wave. Breakdown then occurs on section A B of the curve.

During the experiments observations were discontinued and the electrodes resurfaced if the field emission current peak much exceeded the capacitance current peak. That is, the current was always less than 50 microamperes.



Graph 6 - 0.5 mm. Steel.

3. 2. 2. The Determination of the Best Method of Conditioning.

Metals in their normal state have adsorbed on their surfaces considerable quantities of gas. This gas has to be removed before the emission characteristics of the actual metal can be obtained. If the metals are suitably treated, for example by heating strongly in high vacuum, this adsorbed gas can be driven off, the amount readsorbed usually being small compared with that initially present. Conditioning processes also tend to remove microscopic surface projections by melting. Table 4 gives the time taken for a monolayer to form on a surface at various pressures, assuming the residual gas is oxygen, and neglecting the fact that some molecules will collide elastically with the surface and escape adsorption.

TABLE 4 (Ref. 54).

Gas Press. No. of Impacts Time taken for gas particles to
mm. Hg. per cm.² per sec. cover completely the target area.

10 ⁻⁵	4 x 10 ¹⁵	0.06 second
10 ⁻⁶	4 x 10 ¹⁴	0.6 "
10 ⁻⁷	4 x 10 ¹³	6.0 "
10 ⁻⁸	4 x 10 ¹²	1 minute
10 ⁻⁹	4 x 10 ¹¹	10 minutes
10 ⁻¹⁰	4 x 10 ¹⁰	100 "
10 ⁻¹¹	4 x 10 ⁹	1000 "

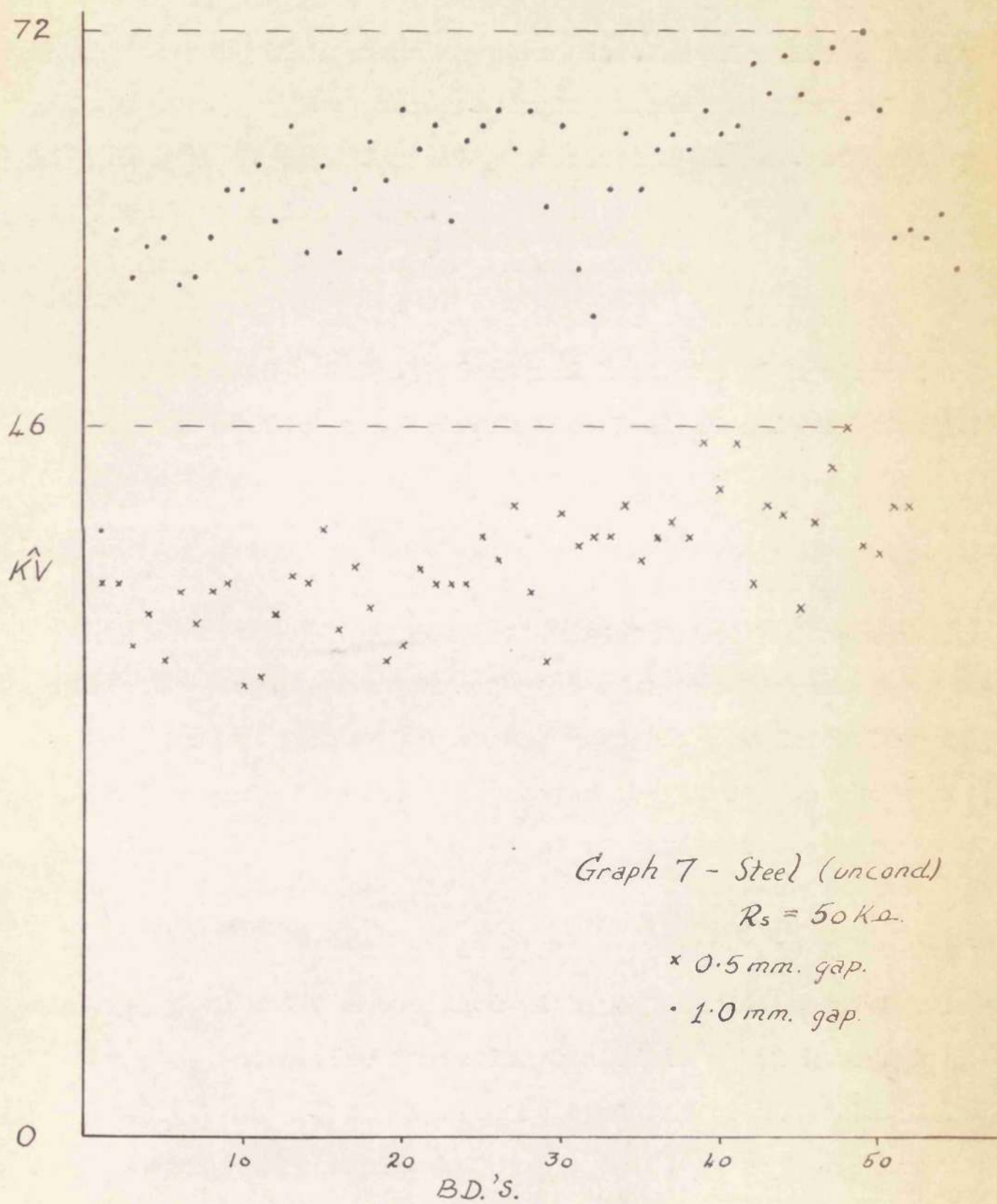
In this study it was decided to try methods which appeared practicable from engineering considerations, and the breakdowns were studied at pressures which were obtainable with care using an engineering high vacuum system (i.e. metal system, rubber gaskets etc.). The pressure during tests was always less than 10^{-5} mm. of mercury and usually nearer 5×10^{-6} mm. of mercury as given by the ion gauge.

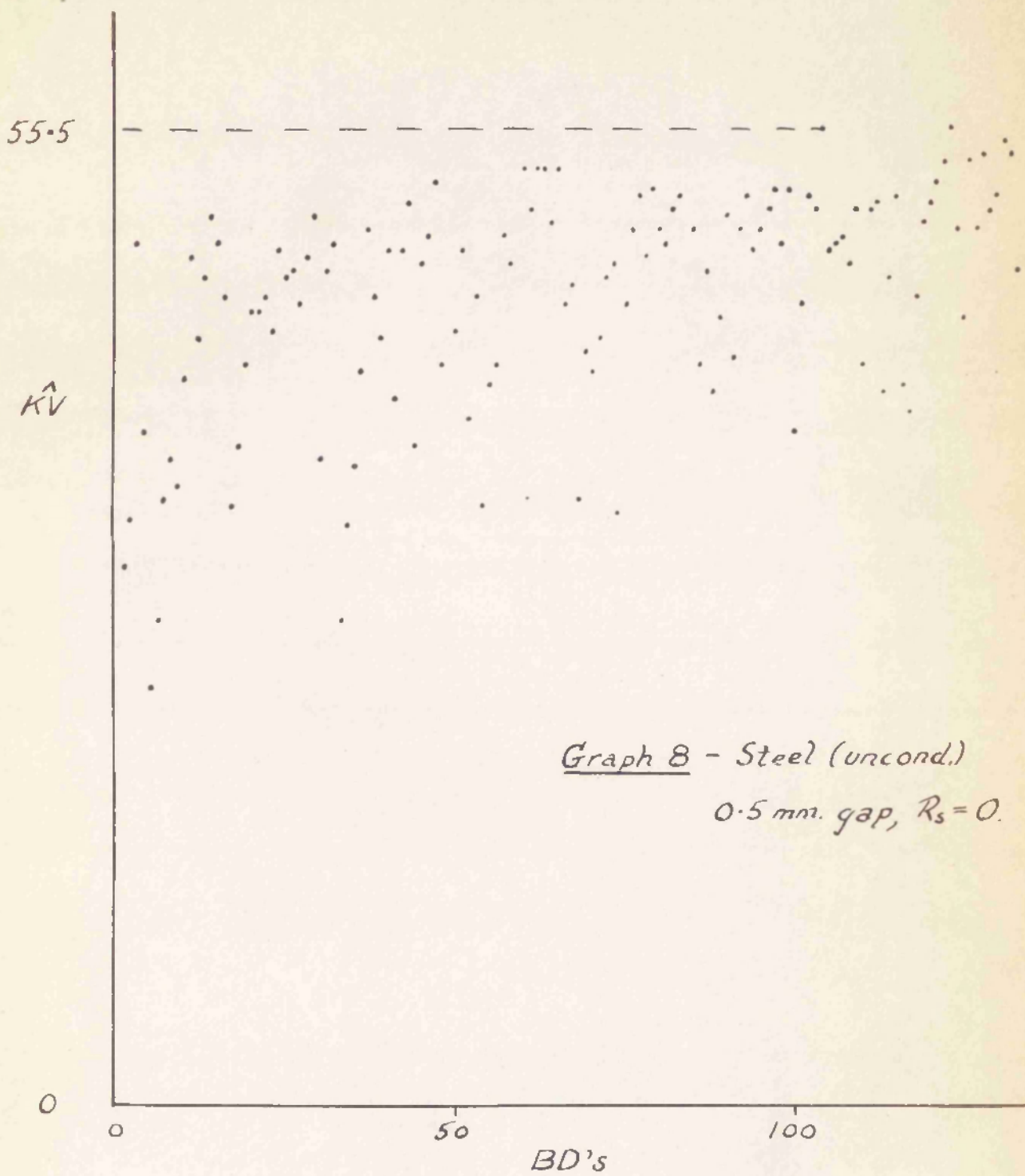
The forms of conditioning examined were

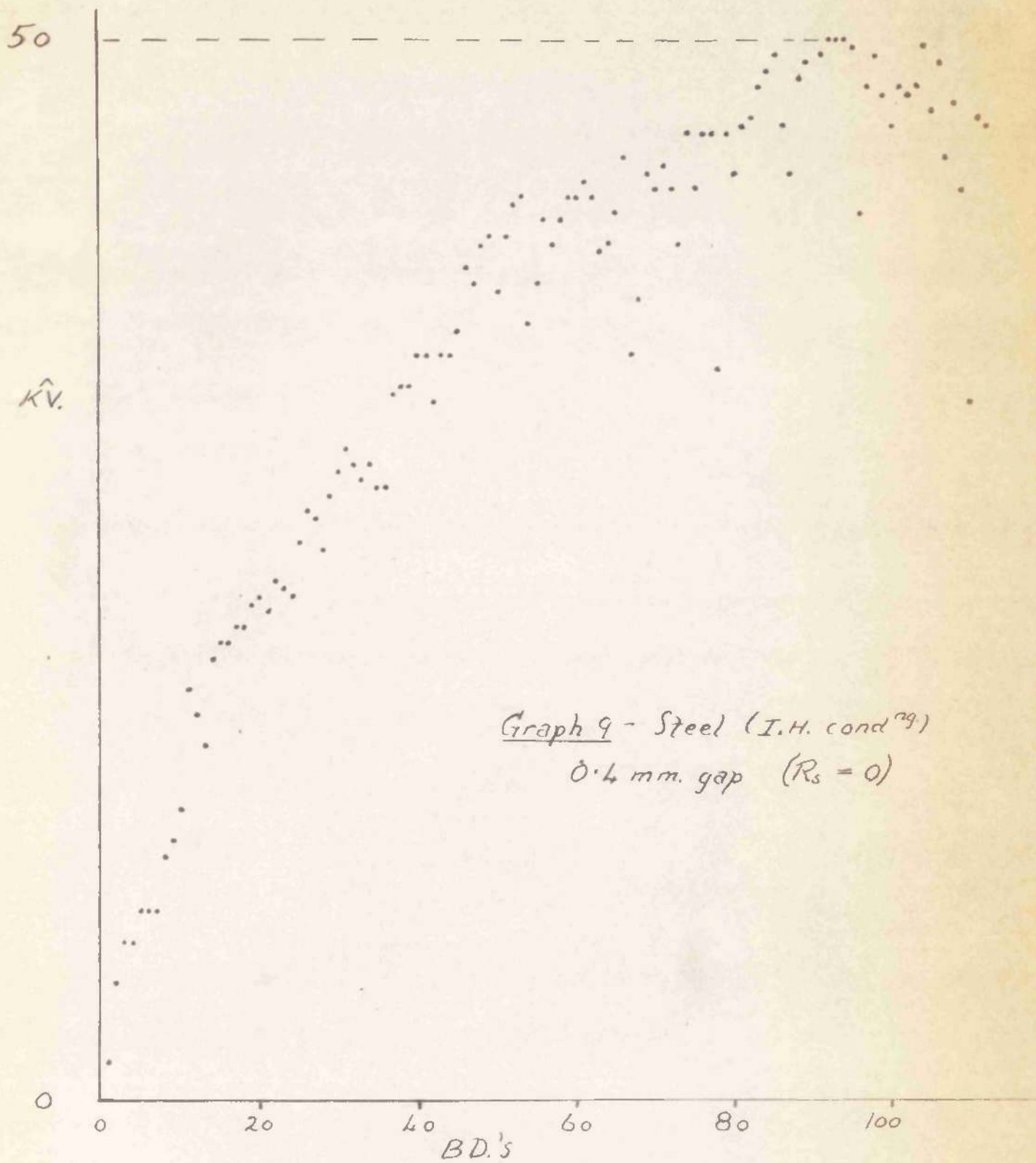
- (a) Induction heating of the electrodes to a temperature of approximately 800°C . (bright red heat) in high vacuum,
- (b) Running a discharge between the electrodes in a hydrogen atmosphere, and
- (c) Process (b) followed by (a).

Graphs 7 and 8 show breakdown tests on unconditioned electrodes which had a buff polish finish and had been well washed in ether. The general rise with breakdowns corresponds to the spark conditioning process used by some investigators, and as one would expect, the greater the energy in the spark, the quicker the rise. The effect of series resistance is discussed more fully later (pages 52 & 53). Graph 8 appears to have reached a plateau but is still approximately 15% below the breakdown voltage obtained with well conditioned electrodes.

The electrodes were induction heated to a bright red heat for various periods of time on several different tests without satisfactory conditioning being obtained. Graph 9 shows the breakdown voltages obtained after heating for one hour at a pressure of 5×10^{-6} mm. of mercury. From this curve it is seen







that the electrode condition after induction heating, compared unfavourably with the experiments in which the electrodes were conditioned only by sparking (graph 8). This was probably due to the pump vapour cracking on coming into contact with the red hot electrodes and leaving a minute carbon deposit which had to be removed by repeated breakdowns.

Anderson (32) found that running a discharge of approximately 0.25 amperes per cm.² between the electrodes for three minutes in a hydrogen atmosphere gave satisfactory results.

In the tests described here the following procedure was employed. The gap was set at approximately 2 mm., the bell jar filled with hydrogen, and a glow discharge produced by applying a variable voltage (50 cycles/sec.) between the electrodes. The pressure of hydrogen in the system was allowed to increase until the glow covered only the opposing faces of the electrodes (approximately 10 mm. of mercury). The applied voltage was then adjusted until the discharge current was one ampere (in the case of steel electrodes - other metals, see later). Plate 2 shows the conditioning taking place. The discharge was maintained for three minutes and the system then pumped to a high vacuum. The phenomenon just described is the normal glow which has a voltage drop nearly independent of the discharge current.

When testing, the peak gap voltage was raised linearly at approximately 6KV/second until breakdown took place. The relay activated by the polarity indicator, would then operate and open the primary circuit of the high voltage transformer.

Graph 10 shows the breakdown voltages obtained in a test with no series resistance. Normally, a plateau region was reached after a few breakdowns. In the more consistent breakdown runs, there would occur an occasional low breakdown voltage, and then one or two rising values before the plateau region was again reached. These sporadic low freaks are apparently caused by the preceding breakdown producing excessive surface roughness, and the rising values correspond to a process of removal. This low value, and any accompanying conditioning breakdowns, was considered as one low freak and disregarded when calculating the mean breakdown voltage and standard deviation. A result below eighty per cent of the maximum breakdown voltage in a test was considered a low freak, and where they were disregarded the number is given as a percentage of the total breakdowns.

Table 5 shows the maximum breakdown voltages obtained in the tests carried out under the circuit conditions specified. Some of the tests were performed in the same experiment - that is, without the electrodes being resurfaced and with the system pressure maintained below 10^{-1} mm. of Hg. These tests bear the same index letter. The suffix indicates the order in which the tests were carried out.

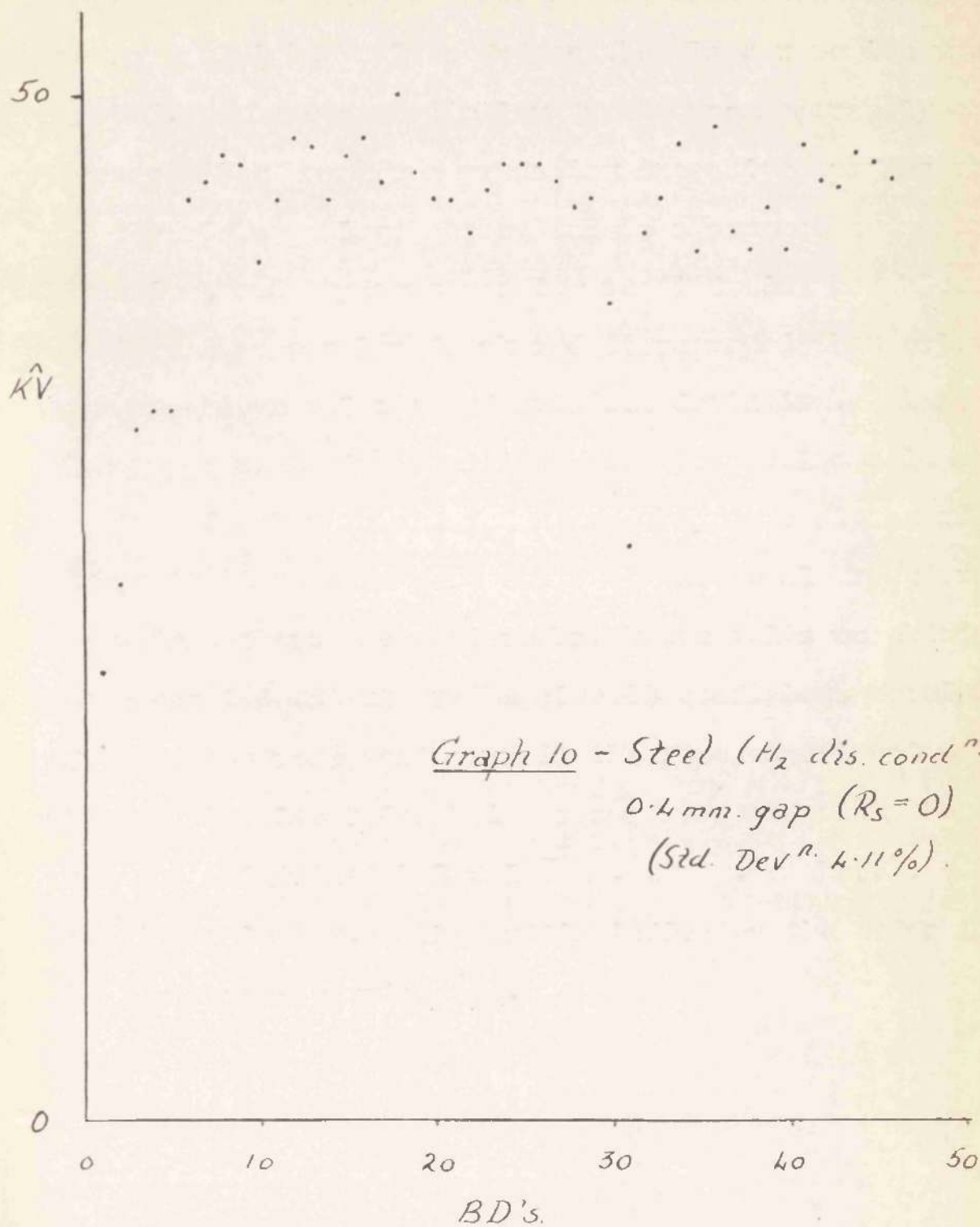


TABLE 5 - STEEL ELECTRODES.

(The tests were carried out after hydrogen discharge conditioning of the electrodes, unless otherwise indicated by the index letter - see pages 49 and 50).

A. 0.4mm. gap.

Index letter	A ₁	B	C	E	F ₁	G ₁	H ₃
Series Resistance (R _S)	0	0	0	0	50K Ω	100K Ω	450K Ω
Max. B.D.V. ($\hat{K}V$.)	53.5	53	53	52	45.5	49.5	50.7
Mean B.D.V. ($\hat{K}V$.)	51.4	48.6	48.2	47	43	38.7	41.4
Std. Dev ⁿ . (% mean)	3.82	4.11	4.5	4.44	3.9	21.6	23.7
% Low freaks	0	7.1	5.4	8.2	12.5	-	-
B.D.'s. to plateau.	30	9	83	36	5	1	2

TABLE 5 - STEEL ELECTRODES (Contd.)

B. 0.5 mm. gap.

Index Letter	A2	F2	G2	H1	H2	J1	J2	K1	K2	K3	K4	K5	K6
Series Res. (R_s)	0	50K Ω	100K Ω	100K Ω	450K Ω	0	0	0	0	0	0	0	50K
Max. B.D.V. ($\hat{K}\hat{V}$.)	62.6	48.3	64.8	63.2	64.5	60.5	61	61.5	65.5	63.5	63.5	63.5	65.5
Mean B.D.V. ($\hat{K}\hat{V}$.)	56.7	44.5	46	45.3	50.5	56.4	55.6	55.8	58.0	46.5	54	52.9	53.3
Std. Dev ⁿ . ($\%$ mean)	4.8	6.55	28	20	15.8	5.5	5.3	7.0	11.4	19.6	13.6	13.7	17.3
$\%$ Low freaks.	8.7	7.3	-	-	-	17	12.8	12	-	-	-	-	-
B.D's to plateau	4	11	3	6	6	4	2	1	4	0	0	1	5
Capacitance added ($\mu\mu f$)	0	0	0	0	0	0	0	0	0	17.5	0	7.5	0

TABLE 5 - STEEL ELECTRODES (Contd.)C. 0.525 mm. gap.

Index Letter	L ₁	L ₂	L ₃
Series Res. (R _s .)	0	0	0
Max. B.D.V. (KV.)	64.5	68.6	67.6
Mean B.D.V. (KV.)	63.6	62.6	61.7
Std. Dev ⁿ . (% mean.)	2.64	6.25	7.00
% Low Freaks.	0	8	6.9
B.D.'s to plateau.	17	0	2
Capacitance added ($\mu\mu\text{f.}$)	0	17.5	0

A - test followed H₂ discharge plus induction heating for half hour and considerable sparking at smaller spacings.

C - test followed induction heating for 1 hour and 83 conditioning sparks to reach plateau.

D - test followed H₂ discharge plus induction heating for 1 hour.

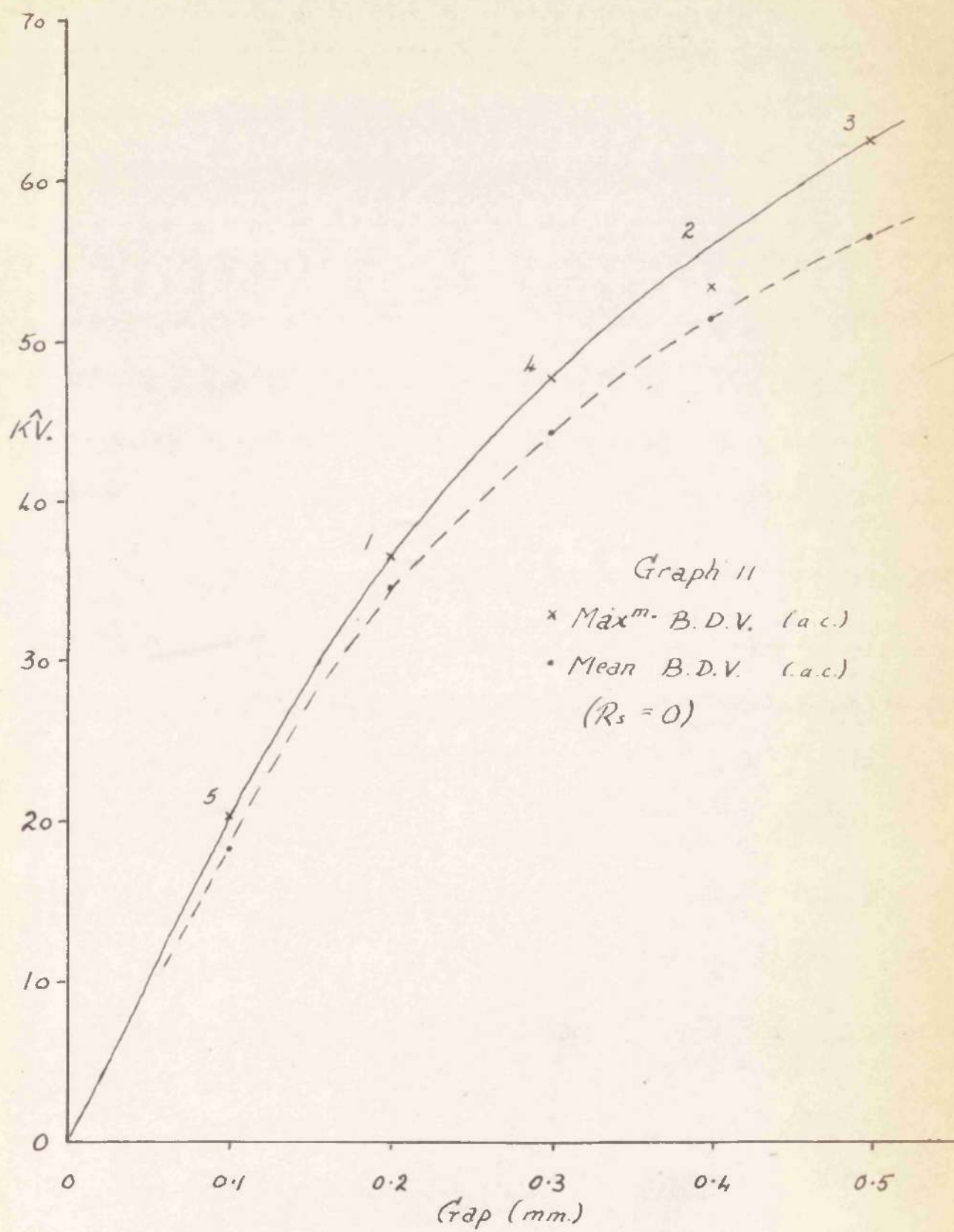
K) tests investigating the effect of gap capacitance.
L)

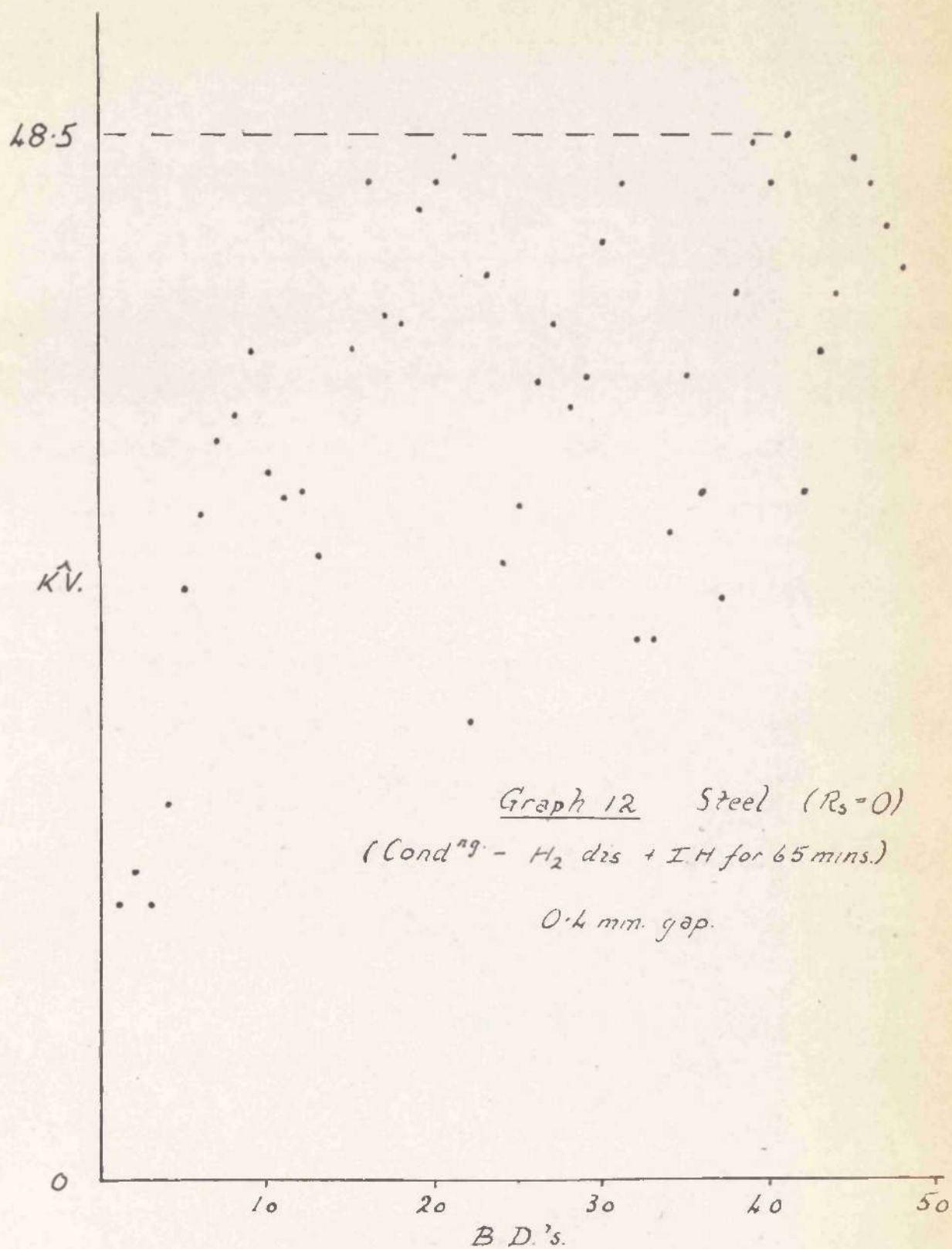
Table 5 shows that the most consistent results were obtained with zero series resistance and the minimum gap capacitance - see tests E, F₁, G₁, H₃ and A₂, F₂, G₂, H₁, H₂. There was no significant difference in consistency between tests having 100K Ω and 450K Ω series resistance, and both consistent and inconsistent results could be obtained (F₁, F₂, K₆) with 50K Ω series resistance. This is discussed under "Other Factors Influencing the Breakdown Voltage" (page 52) and was later clarified by oscillographic measurements on the discharge current under d.c. conditions (page 74).

The large scatter in tests K₂, K₃, K₄ and K₅ was apparently due to added gap capacitance. Graph 11 shows the relationship between breakdown voltage and gap spacing.

Conditioning by induction heating in high vacuum after the hydrogen discharge, was tried. It was thought possible that the hydrogen discharge would replace the adsorbed gases with hydrogen which would in turn be removed by heating. The induction heating impaired the electrode condition (graph 12, cf. graph 10) due, probably, to a carbon deposit on the surfaces as suggested previously.

These experiments showed that the best method of conditioning was by hydrogen discharge, and this process was used, unless otherwise specified, in all subsequent experiments.





3. 2. 3. Other Factors Influencing the Breakdown Voltage.

During the many experiments using steel electrodes, it was found that the resistance in series with the gap had a considerable bearing on the spread of the results. Increasing the resistance gave a greater scatter. The most consistent results were obtained when the series resistance was nominally zero.

It is thought that the spark can be considered in two parts:-

- (a) the discharge of the gap and associated capacitance,
- (b) the discharge of the capacitance C . (fig. 5).

The discharge of the gap capacitance and the breakdown mechanism itself produce a certain surface roughening which can be smoothed by melting if the 'follow' current from the capacitance C is large enough. This is in agreement with the electron microscopy studies of Haefer (55), who found that sharp points could be smoothed by sufficiently large electron emission from the projections. The greater the surface roughening the more likely is a low breakdown voltage to follow. Plates 3 and 4 show typical cathode marks obtained with high, and low, series resistance respectively. This is further clarified by the oscillograph studies on d.c. (section 4.4.)

Graphs 13 and 14 are from experiments in which capacitance was put across the gap during the breakdown run as indicated, and it is seen that the scatter of the results is increased. Removing the added capacitance does not restore the situation completely, due, probably, to the roughened state of the surfaces consequent upon the breakdowns with the larger capacitance.

68.6

KV.

17.5 pf. across
gap.

Graph 13 - Steel (H_2 dis. cond^{ng})

0.525 mm gap ($R_s = 0$)

The effect of gap capacitance:

0

20

40

60

80

BD's

65.5

KV

17.5 pf. across
gap

Graph 14 - Steel (H_2 dis. cond^{ng}.)

0.5 mm. gap ($R_s = 0$)

The effect of gap capacitance.

0

0

20

40

60

80

100

B.D.'s

Graph 15 shows a breakdown run, erratic due to large gap capacitance, with series resistance added at the point shown. The deterioration in the level and consistency of the breakdown voltage is obvious and typical. The standard deviation figures on Table 5 also indicate the effect of series resistance.

Due to the roughened state of the electrode surfaces, a large prebreakdown current, which increased quickly with the number of breakdowns, was associated with tests having resistance in series with the gap ($50\text{K}\Omega$ -- $10\text{M}\Omega$). This current, which was less than fifty microamperes when the series resistance was almost zero, could be of the order of hundreds of microamperes.

To determine the effect of the pump vapour on the breakdown voltage, a cold trap was fitted to the high vacuum line between the diffusion pump inlet and the vacuum chamber. A cold mixture of acetone and solid carbon dioxide was used, and the trap temperature continuously monitored using a thermocouple. During the test the cold trap temperature rose from -78°C to -75°C .

The figures for the test are shown on table 6, where it is seen that the maximum breakdown voltage is 71KV ., or 8.4% above the largest breakdown voltage previously obtained (see table 5). This test was characterised by an unusually large number of low freaks due, possibly, to the larger spark energies consequent upon the higher breakdown voltages. It is seen that with steel electrodes, the presence of apiezon oil vapour lowers the breakdown voltage by a small amount.

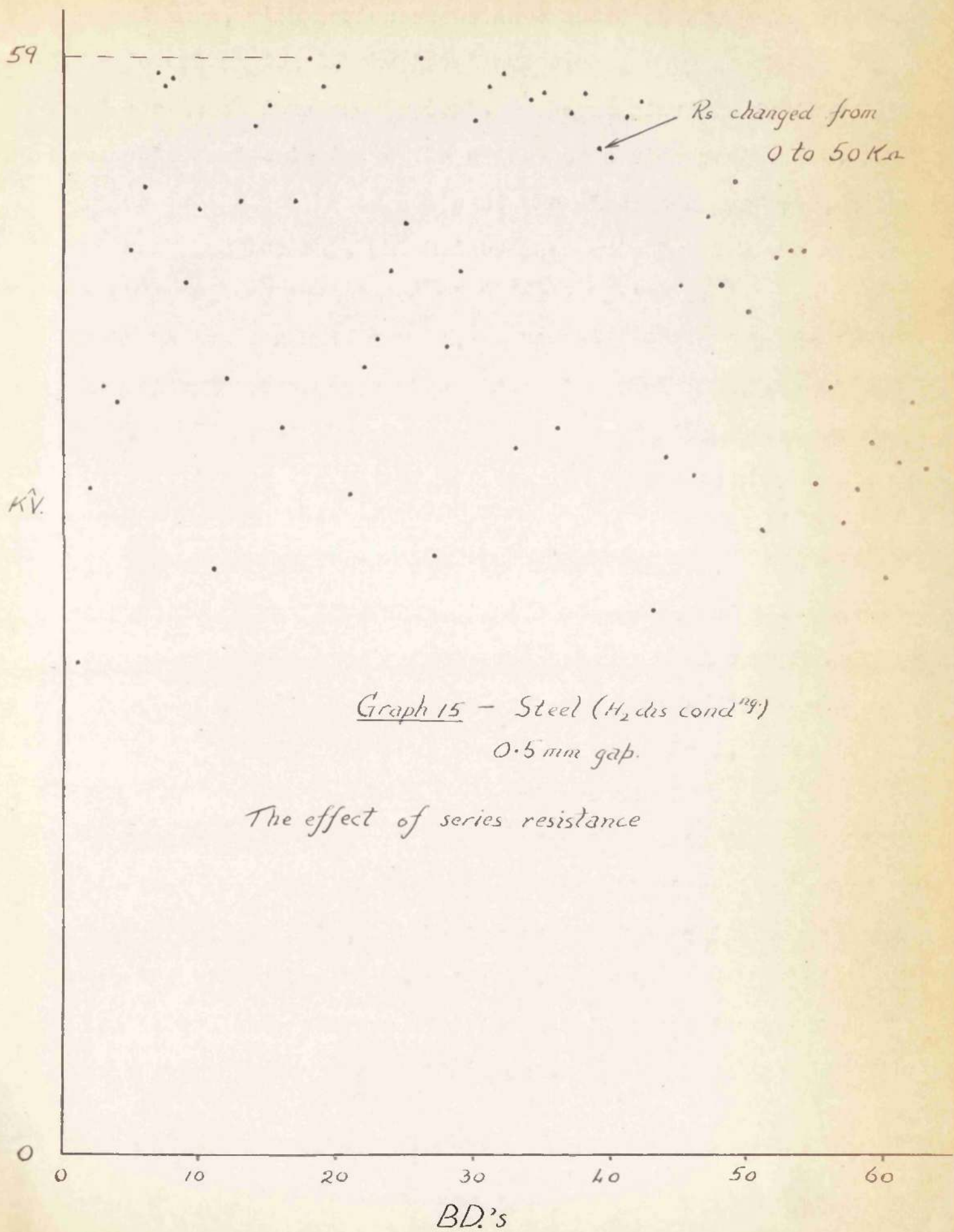


TABLE 6. Steel Electrodes, Cold Trap Test.

0.5mm. gap. (Hydrogen Discharge Conditioning).

Series Res. (R_s .)	0
Max. B.D.V. ($\hat{K}V$.)	71
Mean B.D.V. ($\hat{K}V$.)	63.5
Std. Dev ⁿ . (% mean)	5.7
% Low Freaks	17
B.D.'s to plateau.	22

3. 3. 1. The Breakdown between Copper Electrodes.

Experiments showed that there were two possible breakdown phenomenon which could occur between copper electrodes. One was that of spark breakdown, which was characterised by complete failure of the gap and was the same as the form experienced with steel. The other was what it is proposed to call, the 'glow breakdown', which was characterised by a transitory glow in the gap and conduction of the order of a few milliamperes or less. It is the former phenomenon which is described in this section.

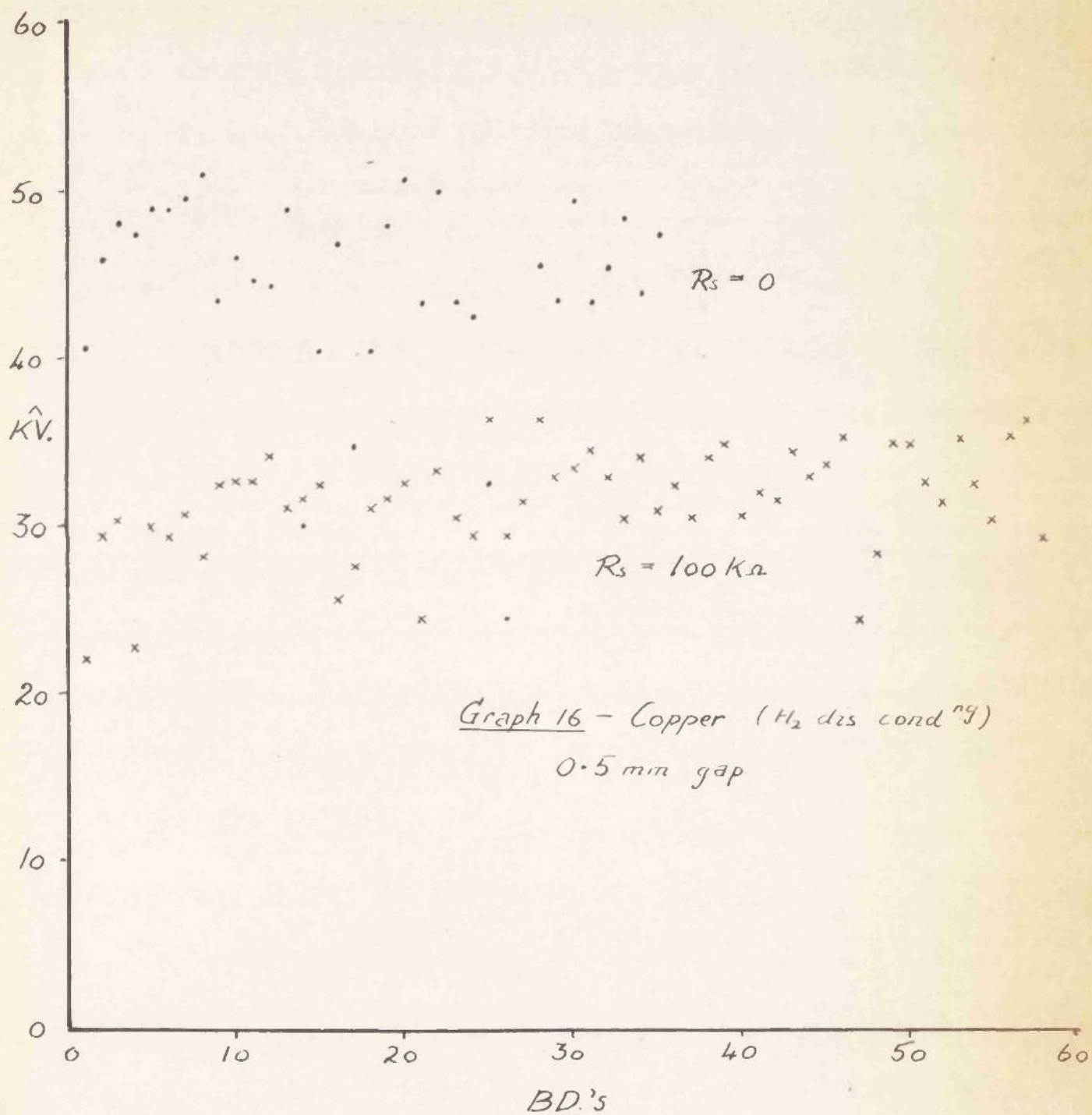
The experiments with steel indicated that the most complete conditioning was obtained by running a hydrogen discharge and this method was used with copper. A discharge current of one ampere, as with steel, produced a powdery ring on the metal surfaces. This ring, which encircled the central region of the electrodes, was composed of sputtered copper which could be readily wiped off. It did not seem to affect the breakdown voltage, which was determined by the condition of the central region. However, a discharge current of 0.5 amperes was used

latterly, which gave satisfactory conditioning without sputtering.

The resistance in series with the gap had a considerable effect on the breakdown figures. With a high resistance, the breakdown voltage attained an apparent plateau which was considerably below that obtained in tests with no series resistance. The results of two tests which show the effect of series resistance are given on graph 16. This effect corresponds to that obtained with steel electrodes.

Graph 17 shows the maximum breakdown voltage curves obtained for copper with two different values of series resistance, and Table 7 gives the standard deviations, etc.

Experiments under cold trap conditions gave no significant increase in the spark breakdown voltage. This is shown by the figures in Table 7.



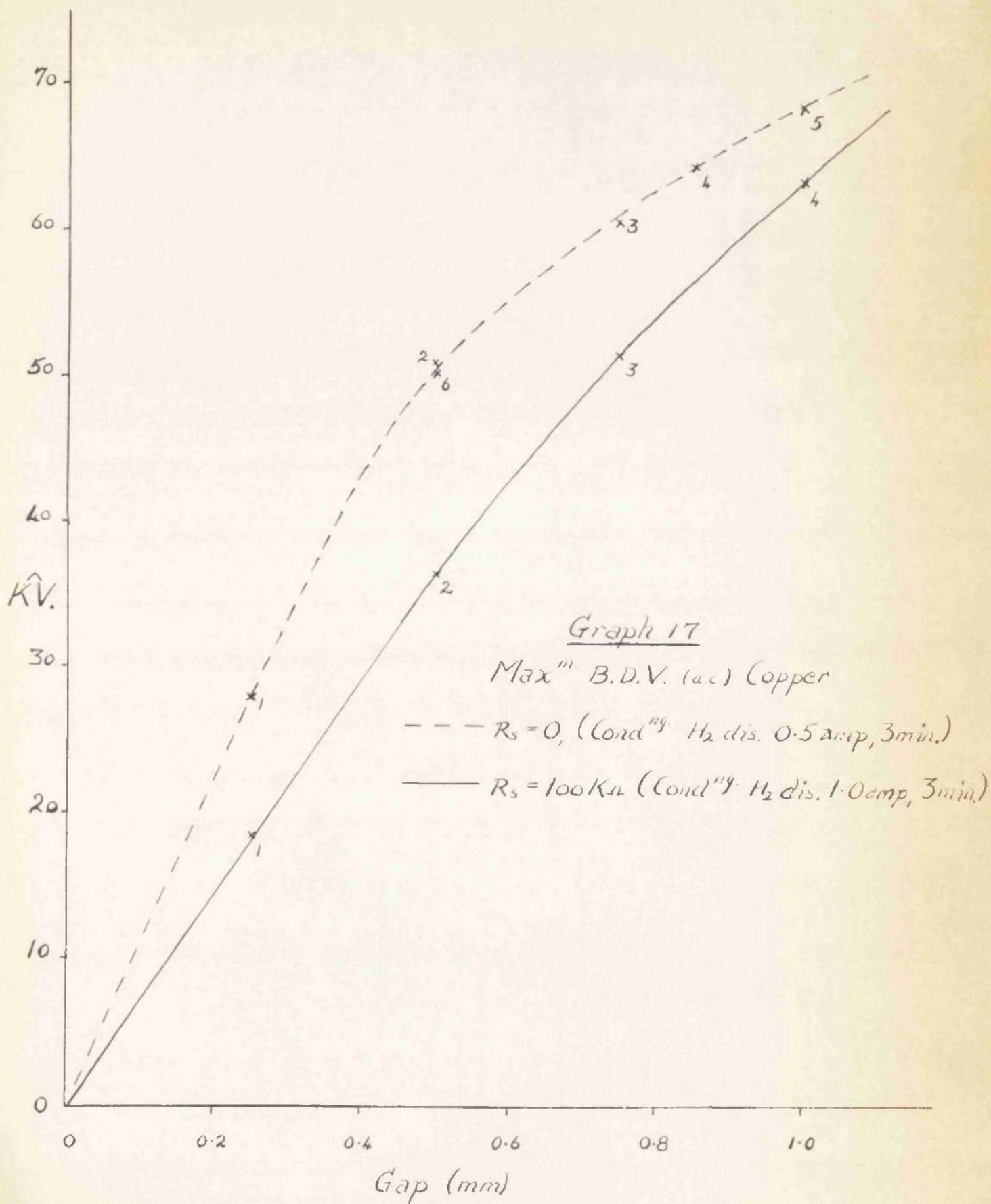


TABLE 7 - COPPER ELECTRODES, SPARK BREAKDOWN.

(HYDROGEN DISCHARGE CONDITIONING).

Index Letter	P ₅	P ₆	P ₇	P ₈	Q ₁	Q ₂	Q ₃	Q ₄	Q ₅	Q ₆	Cold Trap	
											R	S
Gap (mm.)	0.25	0.5	0.75	1.0	0.25	0.5	0.75	0.85	1.0	0.5	1.0	0.5
Series Res. (R _s)	100K	100K	100K	100K	0	0	0	0	0	0	0	0
Max. B.D.V. (KV)	18.5	36.4	51.4	63.6	28	51	60.8	64.5	68.4	50.2	61.1*	48.1
Mean B.D.V. (KV)	15.6	32.5	45.3	65.0	24.3	46	56.6	61.7	65.7	45.5	57.2	44.7
Std. Dev ⁿ . (%mean)	10.8	5.9	6.1	5.35	6.3	4.2	5.1	3.5	3.6	6.3	3.8	6.1
% Low freaks	-	10	16.7	5.3	18	8.8	13.8	13.5	3.2	7.7	2.4	5.9
B.D's to plateau	9	1	0	0	6	0	0	0	0	2	2	21

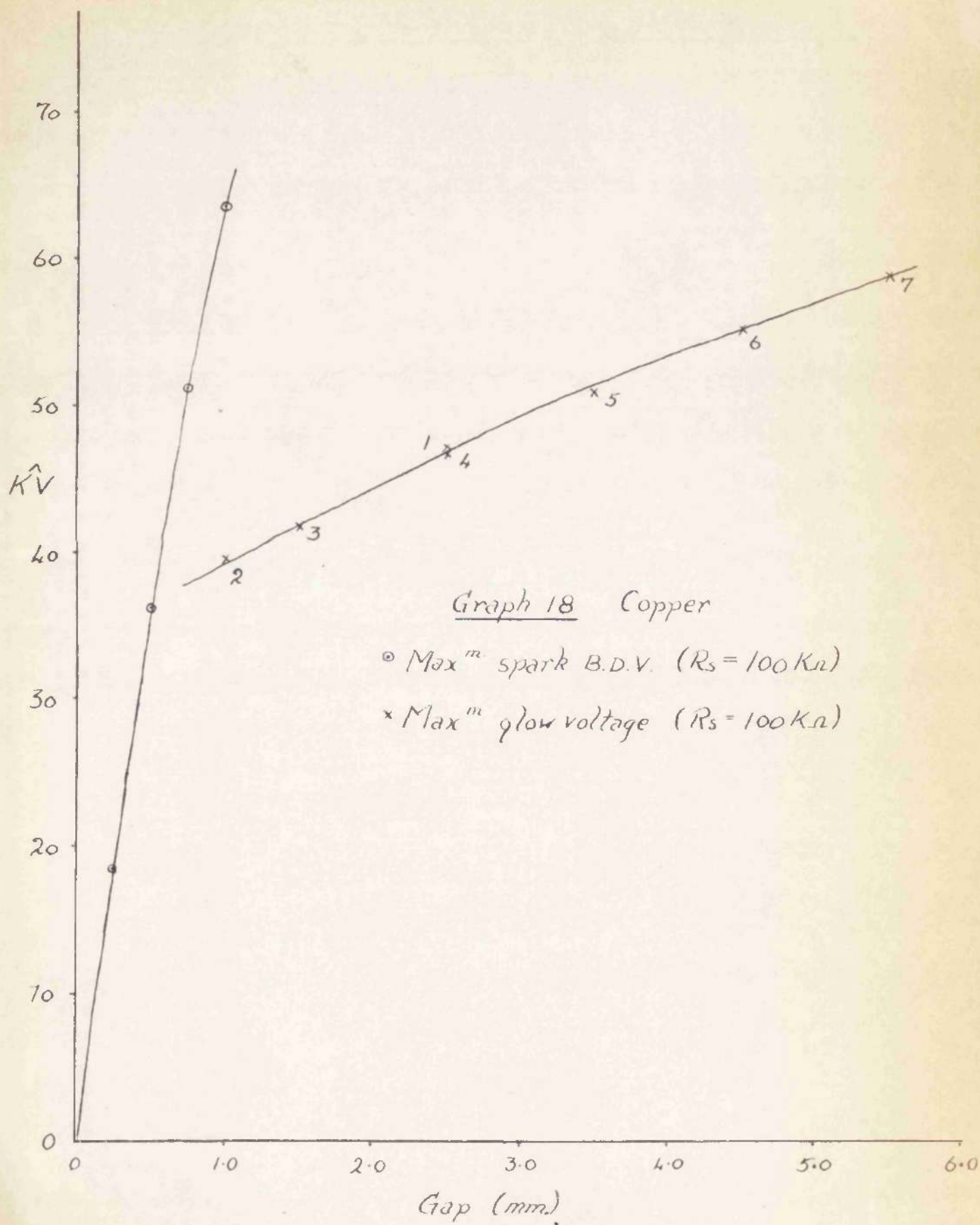
* The maximum breakdown voltage obtained in decay curve tests (next section - glow breakdown phenomenon) with the cold trap was 69.8KV.

3. 3. 2. The 'Glow Breakdown' between Copper Electrodes.

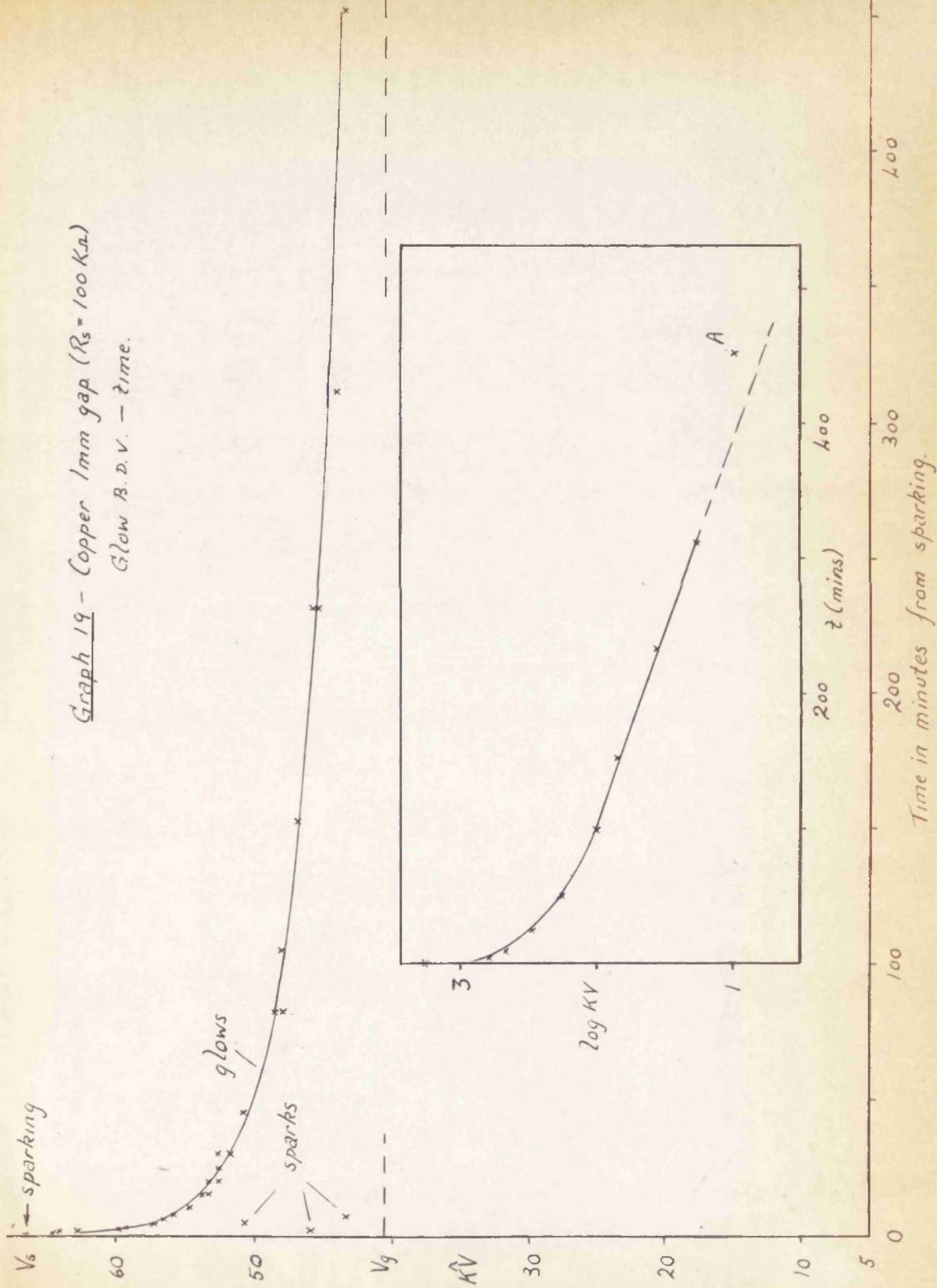
This phenomenon has been experienced with copper electrodes at spacings from one millimetre up to the maximum at which the equipment could be set (5.5mm). At breakdown, a faint, blue, diffuse glow appeared in the gap, accompanied by a fluorescing of the walls of the glass bell jar due to irradiation. This is shown on plate 5 together with another phenomenon which sometimes was visible. This other phenomenon was a form of current leakage (order of 1 micro-ampere or less) which occurred down one, or more, of the polystyrene rods inside the high vacuum chamber, and was characterised by a persistent glow at the negative end of the rod. The current which flowed at glow breakdown was of the order of 2 - 3 milliamperes and will be discussed more fully later in the section on d.c. breakdown.

Glow breakdown occurred at about the same voltage for a given spacing. The breakdown voltage in any test was very consistent and not affected by the value of the series resistance (Table 8). Graph 18 shows the relationship between the 'glow voltage' and the gap spacing, together with the corresponding spark breakdown curve.

If the gap voltage was raised above that at which the glow initially occurred, it was found that after some glow breakdowns the initial glow voltage would have risen to the new value. The breakdown voltage could be raised in this way to the point where spark breakdowns occurred. The glow voltage thereafter fell with time to the value obtained initially (graph 19). Any low, breakdown values which did not lie on this curve were seen to be of the spark type. This consistent decay curve could

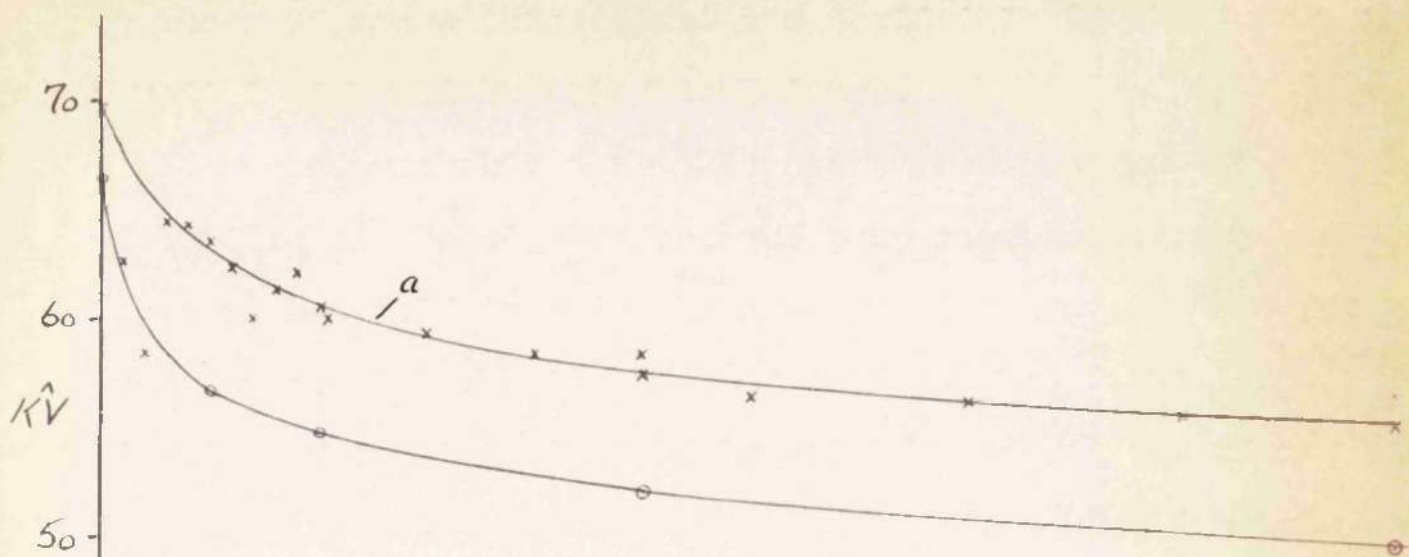


Graph 19 - Copper 1mm gap ($R_s = 100 \text{ K}\Omega$)
Glow B. D. V. - time.



not be obtained without high series resistance. Apparently, the occasional sparks which occurred had a conditioning effect on the surfaces - this effect was negligible if the spark energy was limited by high series resistance.

It seemed probable that this phenomenon was caused by adsorption on the electrodes, and pump vapour was suspected. Tests with a cold trap in the system still showed glow type breakdowns, although the rate of fall of the glow voltage with time, after conditioning to the sparking point, was slower and less consistent. (see graph 20). This increased inconsistency was probably due to the breakdown voltage remaining for a longer time near the spark breakdown level. Even the interposition of the trap in the system without refrigerant gave a decay curve similar to graph 20a. This was due, presumably, to the improved baffling between the diffusion pump and the high vacuum chamber. The glow breakdown for a given gap occurred at a higher voltage under cold trap conditions. (Table 8). These tests indicated that the adsorption of pump vapour played a major part in this phenomenon, but a more complicated vacuum system with a baffle valve, bypass line, and preferably liquid air rather than 'drikold', would be necessary to show that the pump vapour was the sole cause.



Graph 20 Copper 1 mm. gap ($R_s = 100 \text{ K}\Omega$)

Glow B.D.V. - time

* with cold trap.

o without cold trap.

Time in minutes from sparking.

TABLE 8 - COPPER ELECTRODES, GLOW BREAKDOWN.

1 mm. gap. (HYDROGEN DISCHARGE CONDITIONING).

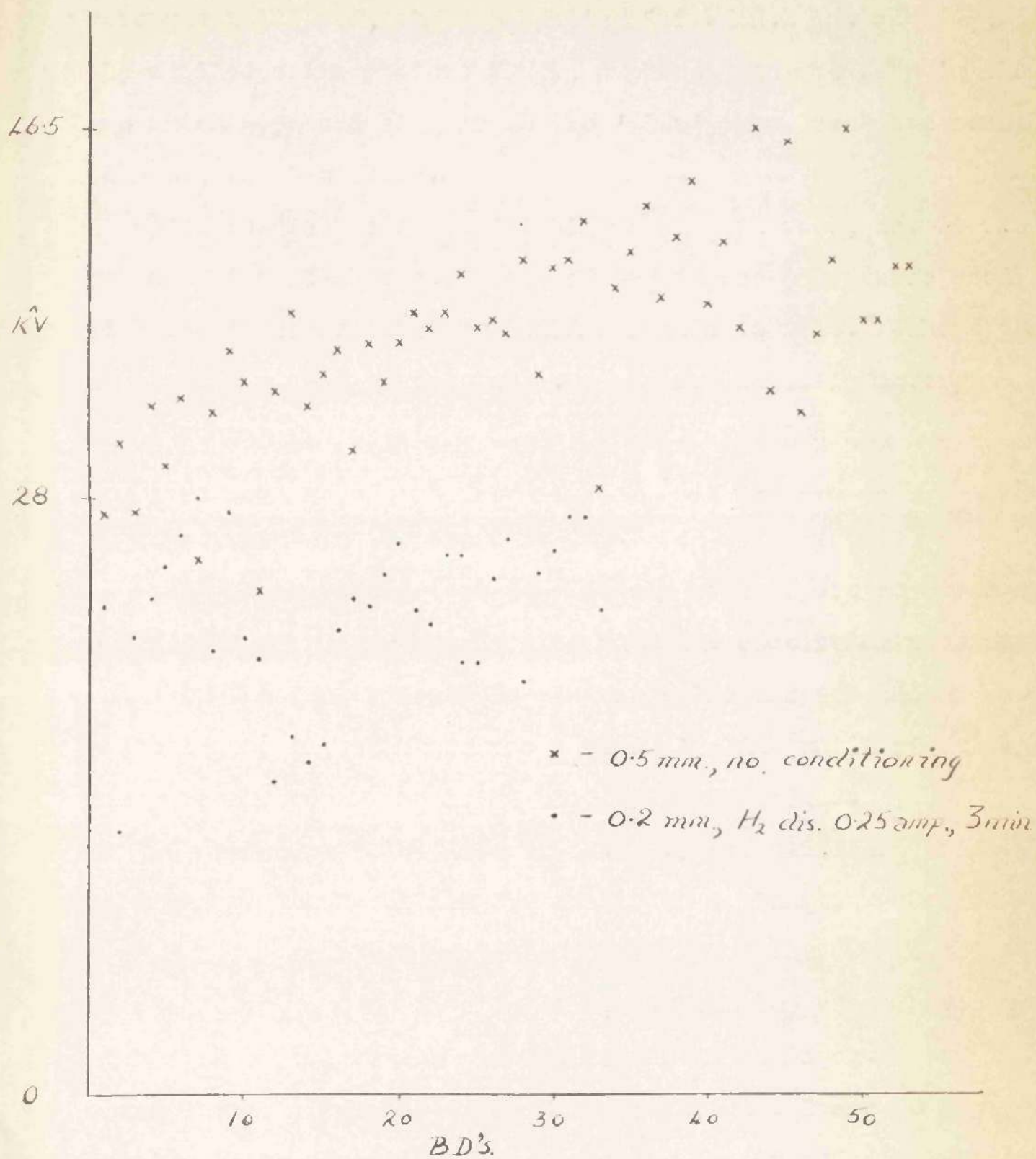
Index Letter.	Cold Trap.										
	P ₁ .	P ₂	P ₃	P ₄	T ₁	V ₁	V ₂	W ₁	W ₂	X ₁	X ₂
Series Res. (R _g .)	100K.	100K.	100K.	100K.	0	0	0	0	100K.	100K.	100K.
Max. B.D.V. (KV.)	40.5	42.8	39.5	39.8	42	39.2	38.5	53.4	53.8	50.7	50.
Mean B.D.V. (KV.)	40.2	42.3	39.0	38.8	41.1	38.9	38.0	53	53	50	49.6
Std. Dev ⁿ . (% mean)	1.2	1.05	0.81	1.5	1.6	0.82	0.75	0.42	1.06	0.28	0.74
% Low freaks.	0	0	0	0	0	0	0	0	0	0	0
B.D's to plateau.	0	0	0	0	0	0	0	0	0	0	0

3. 4. 1. The Breakdown between Aluminium Electrodes.

The discharge phenomenon studied with aluminium electrodes was that of spark breakdown. On one occasion when the electrodes were unconditioned, the gap spacing large (5.5 mm. approx), and the applied voltage about 70KV., a phenomenon was seen in the gap which appeared similar to the 'glow' type breakdown seen with copper electrodes.

Hydrogen discharge conditioning was again used, but it was found that a discharge current of one ampere (the value used with steel) caused the aluminium surfaces to melt. There was no melting with a current of 0.25 ampere and satisfactory conditioning was obtained with the discharge lasting for three minutes. Allowing the discharge to last for six minutes gave no improvement in the conditioning.

Graph 21 shows one test immediately after hydrogen discharge conditioning and another started with the electrodes unconditioned. In the former test the plateau value was reached at once, while in the latter there was a gradual climb until after about forty breakdowns an apparent plateau was attained. The maximum value on this plateau (46.5KV.) was still 10% below the maximum breakdown voltage for conditioned aluminium electrodes (graph 22). Table 9 presents a summary of the data obtained on aluminium, and it is seen that, as with copper and steel, high series resistance gave low breakdown voltages. Graph 22 shows the relationship of maximum breakdown voltage to gap spacing. The corresponding curves for copper and steel have been added for comparison.



Graph 21 - Aluminum. ($R_s = 0$)

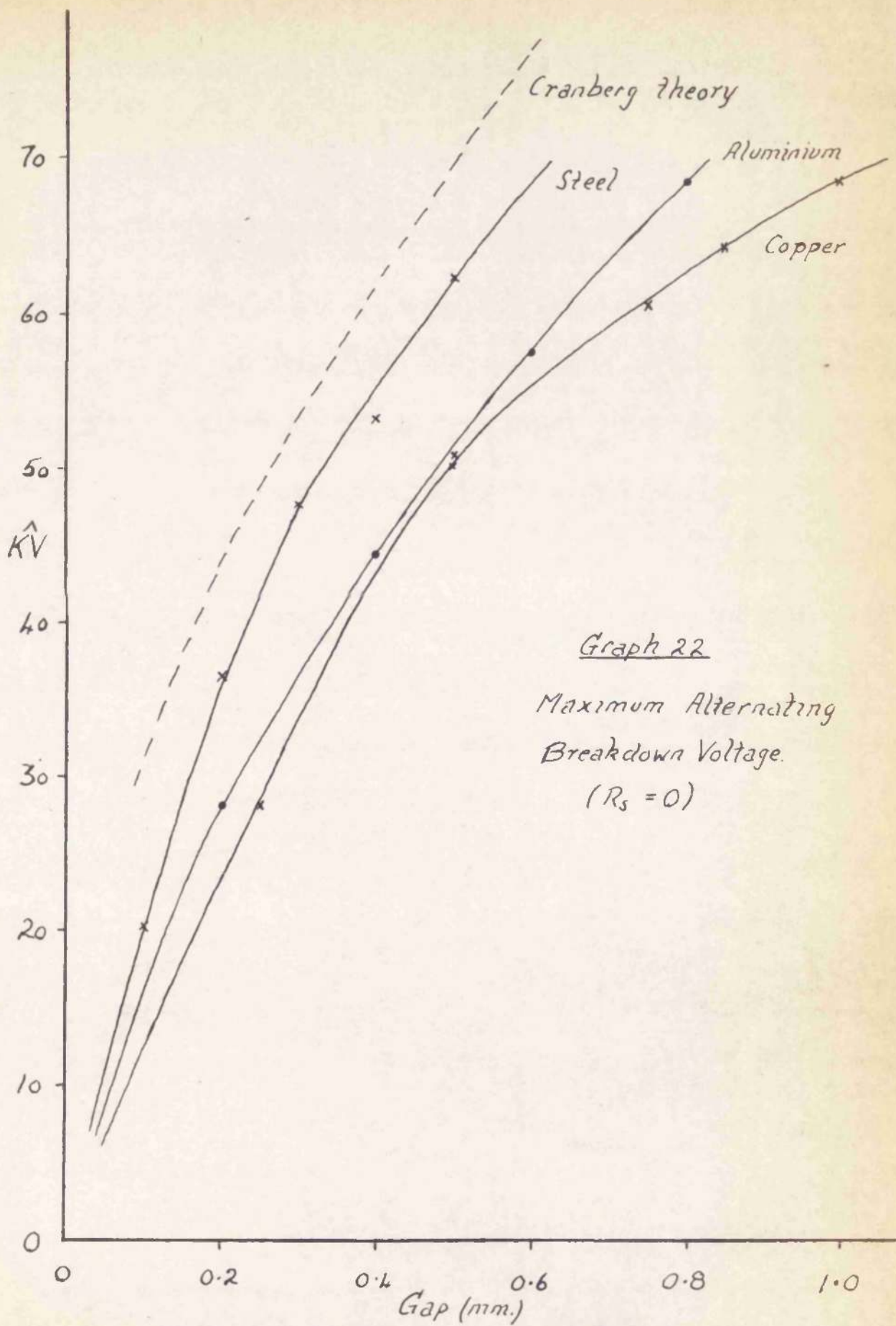


TABLE 9 - ALUMINIUM ELECTRODES (HYDROGEN DISCHARGE CONDITIONING).

Index Letter	Y ₁	Y ₂	Y ₃	Y ₄	Y ₅	Y ₆	Z ₁	Z ₂	Z ₃	D ₁	D ₂	D ₃	D ₄	D ₅
Gap (mm.)	0.2	0.4	0.6	0.8	0.1	0.2	0.2	0.4	0.6	0.2	0.4	0.6	0.7	0.8
Series Res. (R _S)	5M	5M	5M	5M	5M	5M	0	0	0	0	0	0	0	0
Max ^m B.D.V. (KV.)	14.6	23	31	47	9.63	13.4	26.2	42.0	56.0	28	44.6	57.5	63.5	68.5
Mean B.D.V. (KV.)	13	19	27.5	43	8.2	12	22.5	38	50.2	24.6	39.5	52.5	57	62.3
Std. Dev ⁿ (% mean)	4.8	5.4	6.7	6.0	5.4	7.3	6.6	6.3	5.5	6.9	6.1	5.0	7.4	5.3
% Low freaks	16.7	5.1	8.9	14	23	11.4	14.7	18.8	13.5	17.4	17.8	26.7	12.3	10.0
B.D's. to plateau	1	1	1	4	6	0	4	2	5	3	0	2	3	1

(Note: Tests Y and D - Hydrogen discharge, 0.25 amp. for 3 mins.

Tests Z - " " 0.25 amp. for 6 mins.)

4. D.C. Breakdown Tests.

4. 1. D.C. Equipment.

The circuitry for the d.c. tests is shown on figure 8. The smoothing was for all practical considerations complete and the ripple was measured to be less than 0.12% peak to peak. The circuit at breakdown corresponded closely to the a.c. circuit - in both cases the condenser C. discharged through resistance R_g and the gap. As in the a.c. tests, it was desirable that the supply should be removed after breakdown had occurred to prevent excessive damage to the electrodes and to give a definite control over the discharge duration. For reasons which become apparent later (section 4. 3.), the relay system had to be stable and unaffected by surges through the mains. The simple battery supplied circuit shown in figure 9 was used and found to be satisfactory. By variation of the resistance R_p . (fig. 8) it was possible to determine the discharge current required to operate the relays.

The direct voltage was measured by means of a high voltage resistance (R_m) and microammeter. This resistance was designed and constructed at a time when it seemed desirable to have facilities for varying the gap series resistance (R_g) over a large range - up to some hundreds of megohms. The only satisfactory point at which to measure the gap voltage with such large series resistance was directly across the gap, and the measuring resistance had accordingly to be much larger than the series resistance. The resistance (R_m) was designed with a nominal value of 2,040 megohm for working at 120KV. It was

constructed of 400 high stability carbon resistors (each of value 5.1 megohm) mounted in series on a paxolin support, which was shaped in such a way that the leakage path was extremely long. The structure was immersed in oil inside a comparatively small porcelain bushing (approx. 30" long and 12" diameter). The resistor and microammeter (as in fig. 8) were calibrated periodically against uniform field gaps. (56). The mean resistance figures obtained from those calibrations are given below, together with the appropriate dates.

<u>Date.</u>	<u>Mean Resistance.</u>	<u>Days from 5/5/53.</u>
5/5/53	2,075 M Ω	0
17/6/53	2,087 M Ω	43
6/7/53	2,117 M Ω	62
11/11/53	2,123 M Ω	190

It is seen that the resistance drifted considerably (2%) over the first two months and then remained fairly constant.

The microammeter could be read to an accuracy of $\pm 1\%$ at the lowest readings taken, and the d.c. voltage measurements are considered accurate to within $\pm 2\%$.

Plate 6 shows the equipment for the d.c. tests. The 2,000 M Ω resistance is contained in the porcelain bushing on the left of the plate. The H.T. transformers, rectifiers, and smoothing can be seen in the background.

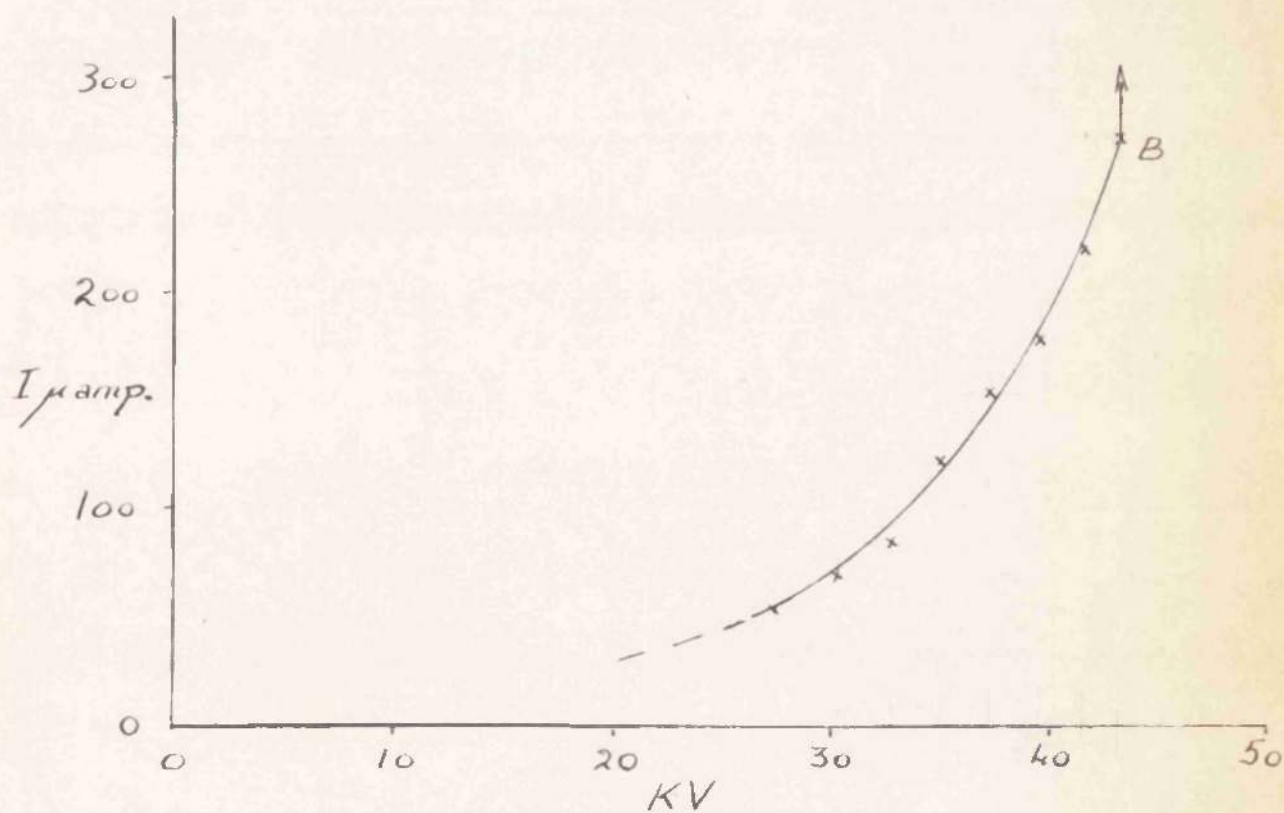
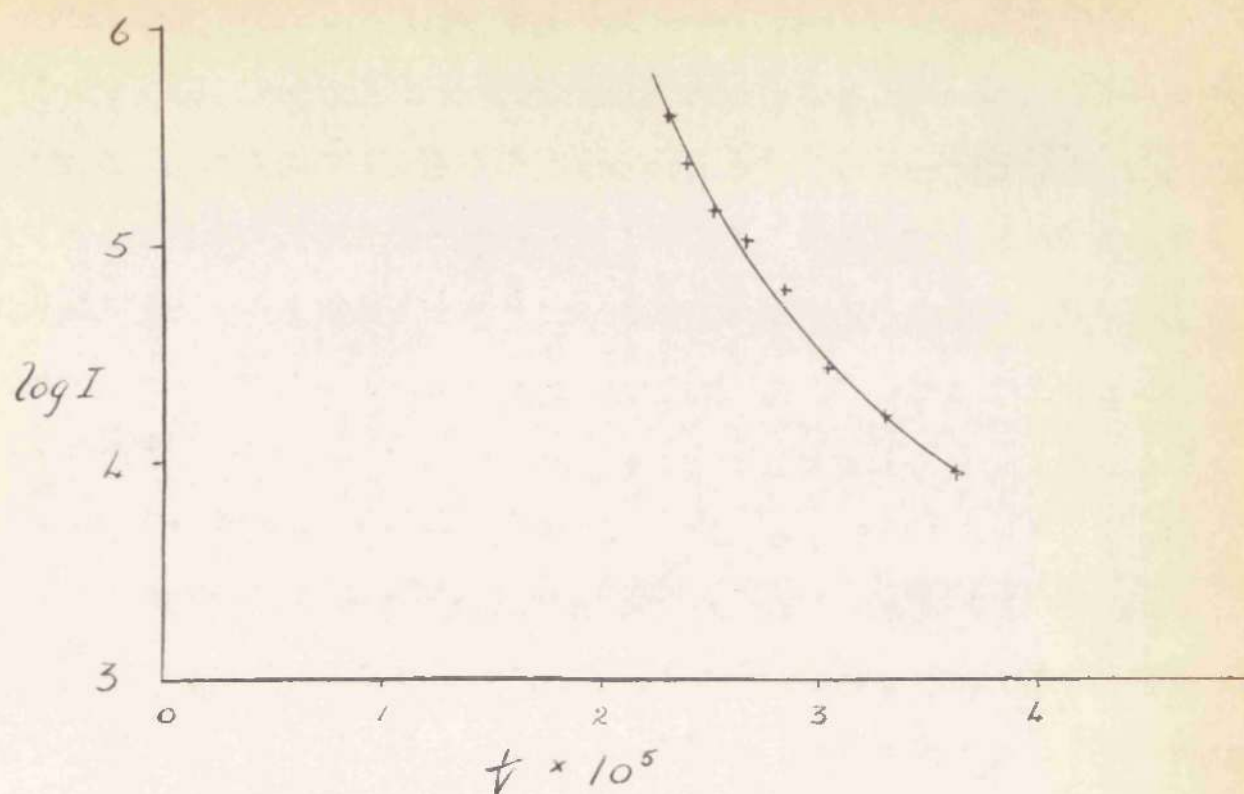
4. 1. The Direct Breakdown Voltage - Steel Electrodes.

The current - voltage characteristic of the gap under d.c. conditions agreed with the findings under a.c. conditions. The characteristic was obtained by driving the variac supplying

the high voltage transformer (fig. 8) with a motor running at a constant speed. The gap voltage thus increased linearly with time, and the voltage across a resistor between the cathode and earth ($R_p = 100K\Omega$) gave a measure of the current. The voltage across this resistor was applied to the plates of a cathode-ray oscillograph which had its time base disconnected, and the movement of the spot was recorded by a motor driven camera. The gap voltage rose from zero to breakdown in approximately 6 seconds. Graph 23 shows the current - voltage relationship derived from the oscillogram after voltage corrections which were necessary because of the high series resistor used. ($R_s = 10M\Omega$). This record was obtained with the electrodes rough. The curve of $\log I - \frac{1}{KV}$ on the same graph does not quite correspond to the linear form expected for field emission (page 1) and it is thought that the slight upcurving at the higher voltage and current values was due to a superimposed thermionic effect at the emitting spot or spots. Dyke and Trolan (50, 51) have shown that currents from a microscopic projection can produce high temperatures due to resistive heating.

As the gap voltage was increased from zero, the current rose as shown on graph 23, the actual value depending mainly on the surface roughness. At a certain point (B) there was a sudden, large increase in the current and normally a spark was seen (plate 7). The voltage at which this occurred is defined as the spark breakdown voltage.

When the breakdown occurred X-rays were radiated from the gap and a geiger counter could be used to determine when the discharge took place. X-ray films were fogged if placed against the



Graph 23

$V - I$ Characteristic, Steel Electrodes, d.c.

outside of the bell jar, but for personal safety it was sufficient to keep approximately 4 feet away from the gap when testing.

Inspection of the electrode surfaces after breakdown showed the following details. -

Cathode: The marks were invariably very small, and microscopic examination showed them to be sharp edged craters about 8×10^{-3} mm in diameter. (plate 8).

Anode: The marks for each breakdown were much larger than those on the cathode and had a diffuse, molten appearance. (plate 9). The larger the gap spacing, the greater the diameter of the melted area. The marks were due to electron bombardment when the spark occurred - the mutual repulsion of the electrons accounting for the comparatively large diameter and also for the increase in diameter with the increase in spacing. On rare occasions in a test a breakdown would occur outwith the central region of the electrodes, and the distance traversed by the spark would be greater than normal. Again, the diameter of the anode mark would be much larger for the greater distance although the discharge voltages would be similar.

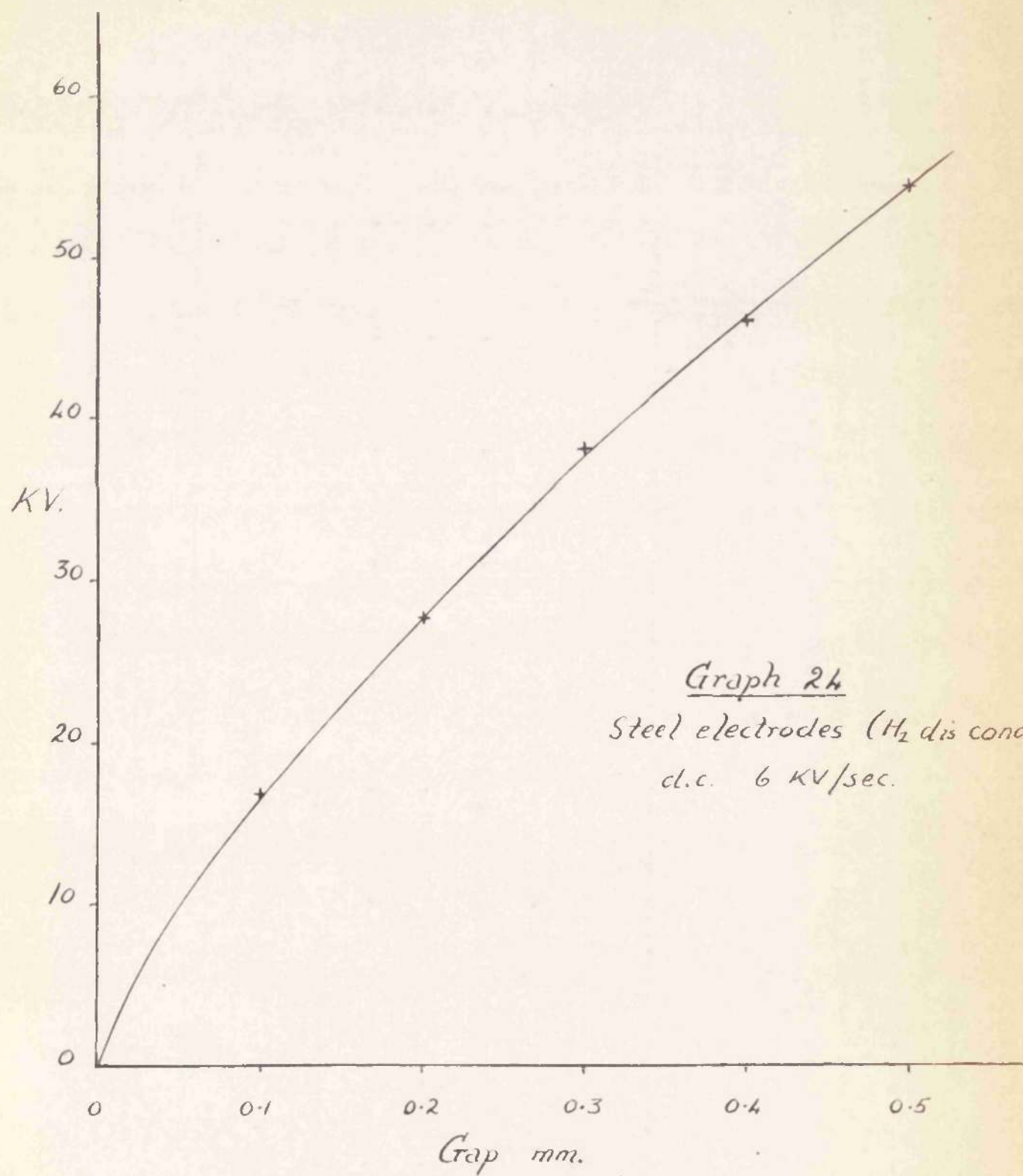
The breakdown voltages in the d.c. experiments were considerably lower than in the a.c. experiments when the gap voltage was raised at approximately the same rate (tables 10 and 11). The consistency in each of the d.c. tests was, in general, better than in the a.c. tests, due probably to the lower breakdown voltage and the smaller capacitive energy in the gap at breakdown. (see page 52). The effect of series resistance on the standard deviation was small, but large resistances gave low breakdown

voltages due to the surface roughness produced. (Table 10, tests A). Graph 24 shows the relationship between the breakdown voltage and gap spacing when the voltage was raised at 6KV per second. The maximum breakdown voltages shown on table 10 are about 15% below those obtained under the corresponding circumstances in a.c. tests (table 5) due to the time effect. This effect was noted on d.c. testing and to a lesser extent on a.c. testing. When the voltage was raised slowly a lower breakdown voltage was obtained than when it was raised quickly. There seemed to be two possible methods of studying this time effect. One was by finding the breakdown voltages for different rates of rise of gap voltage. It was felt that curves obtained in this way would be of little practical importance and fundamentally dependent on the figures supplied by the other method which would determine the time between the application of a fixed voltage and breakdown. Consequently the procedure described in the next section was adopted.

TABLE 10 - STEEL ELECTRODES,

0.5mm. gap. (hydrogen discharge conditioning).

Index Letter.	A ₁	A ₂	A ₃	A ₄	A ₅	B ₁	B ₂	B ₃	B ₄	C ₁	C ₂
Series Resistance(R _s)	11K Ω	1.2K Ω	100 Ω	0	11K Ω	100 Ω	100 Ω	0	0	0	0
Max. B.D.V.(KV).	47.5	46.5	48.5	48.5	46.5	50.5	51.0	55.5	55.5	54.5	56
Mean B.D.V.(KV).	44	44.6	45	46	41	47.3	48.3	52.2	52.5	50.9	51.5
Std. Dev ⁿ .(% mean).	5.3	3.66	3.8	3.2	7.0	5.4	4.4	3.8	5.2	4.3	6.1
% Low Freaks.	4.9	0	0	0	0	0	0	0	0	0	0
B.D's to plateau.	3	1	2	0	2	1	2	0	0	1	1



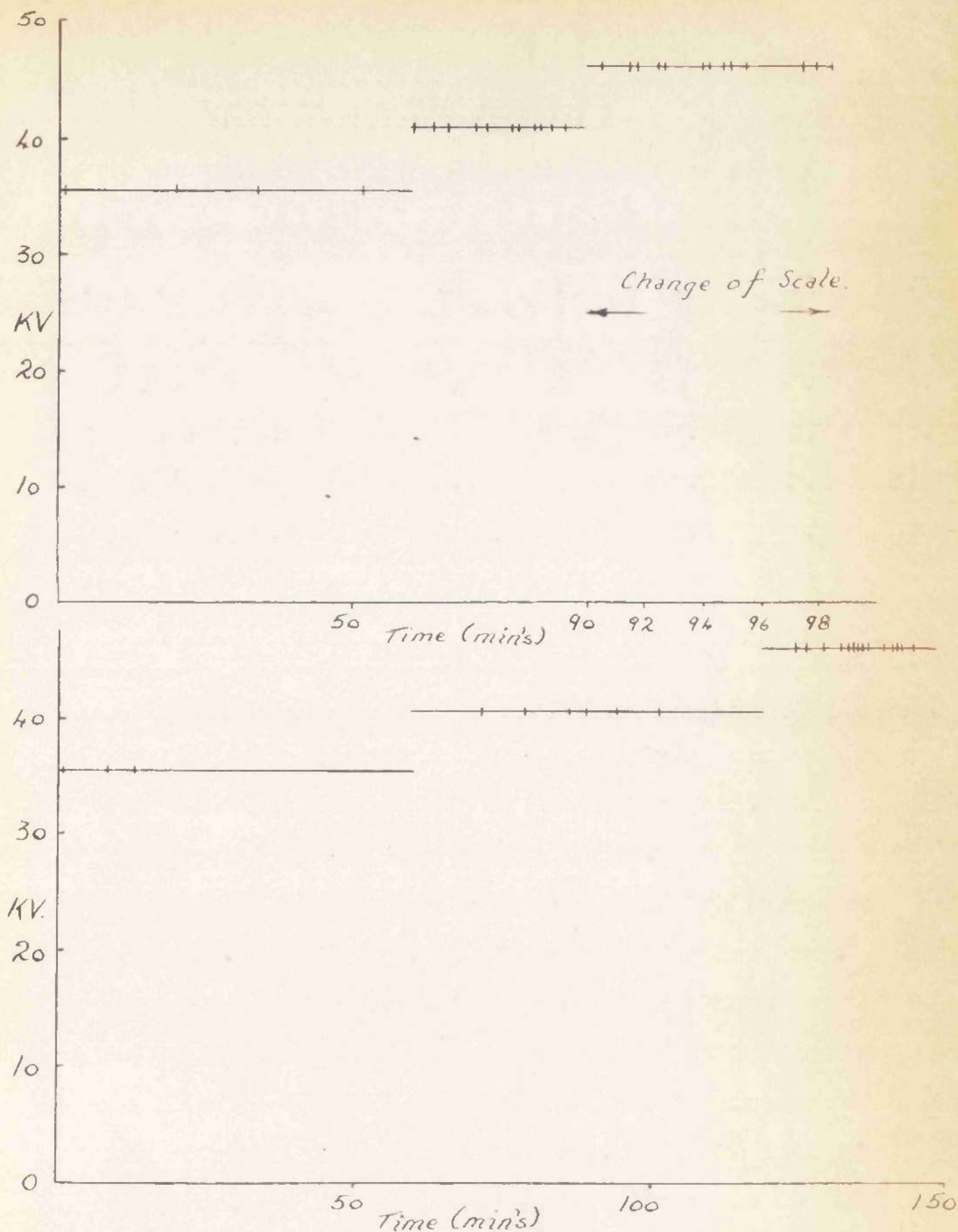
Graph 24
Steel electrodes (H_2 dis cond^{ng})
d.c. 6 KV/sec.

TABLE 11 - STEEL ELECTRODES,
(hydrogen discharge conditioning.)

Index Letter	D ₁	D ₂	D ₃	D ₄	D ₅
Gap. (mm.)	0.5	0.4	0.3	0.2	0.1
Series Resistance (R _s)	0	0	0	0	0
Max B.D.V.(KV).	54.5	46	38	27.7	16.8
Mean B.D.V. (KV).	53	43.9	37.0	26.7	14.2
Std. Dev ⁿ ·(% mean)	3.6	4	2.9	3.4	6.16
% Low Freaks.	7	0	3.3	3.5	3.3
B.D.'s to plateau.	1	1	2	1	1

4. 3. Breakdown and the Time Effect: Steel, Copper & Aluminium.

The time tests were carried out by applying across the gap a voltage which was considerably below (25% approx.) that at which the first breakdown was expected to occur. This voltage was applied for a specific time (one hour) and then increased by a small amount (usually 5KV) and left for a further hour. The gap voltage was raised in this way until breakdown took place, and the times at which this and the subsequent breakdowns occurred were noted. The voltage was increased in steps until the sparking rate was about two per minute. As the rate of sparking increased, the time for which the voltage was applied was correspondingly decreased to prevent, as far as possible, excessive surface damage. Graph 25 shows two typical sets of results.



Graph 25 - Steel 0.5 mm gap (H_2 dis. cond^{ng})
The Occurrence of BD's. at Fixed Voltages.

One hour was decided upon as the initial time for which the voltage should be applied, as any appreciably longer period would give tests lasting for days and was impracticable. The form of the curves of breakdown rate to voltage subsequently obtained seemed to indicate that if the breakdown did not occur in one hour it was unlikely to occur in one day.

Before each test the electrodes were resurfaced and washed in ether. Initially, hydrogen discharge conditioning was used as in the previous experiments, but it was later found that for the time tests no improvement was obtained by conditioning in this way - in fact, the opposite tended to be the case. It is thought that the hydrogen discharge produce a few sputtered particles which gave an initial breakdown voltage lower than that in an unconditioned test. In the earlier experiments which used electrodes conditioned by hydrogen discharge, the few low breakdowns were accounted for under the heading "number of breakdowns to plateau".

Graph 26 shows typical rate of sparking curves obtained for steel at gaps of 0.5mm. It was obvious during the tests that a spark could influence the succeeding rate of sparking by producing surface roughness. This was shown clearly in some of the tests when rate of sparking increased with time at a given voltage. Curve D on graph 26 shows (points 4 and 5) that a rougher surface had produced a greater number of sparks per hour, but the curve also indicates that the voltage still had a considerable bearing on the rate. That is, the sparking rate does not increase with voltage merely because of the increasing number of preceding sparks.

Graph 26 Steel electrodes

A - 0.5 mm. (cond.)

C - 0.5 mm (uncond.)

D - 0.25 mm (uncond.)

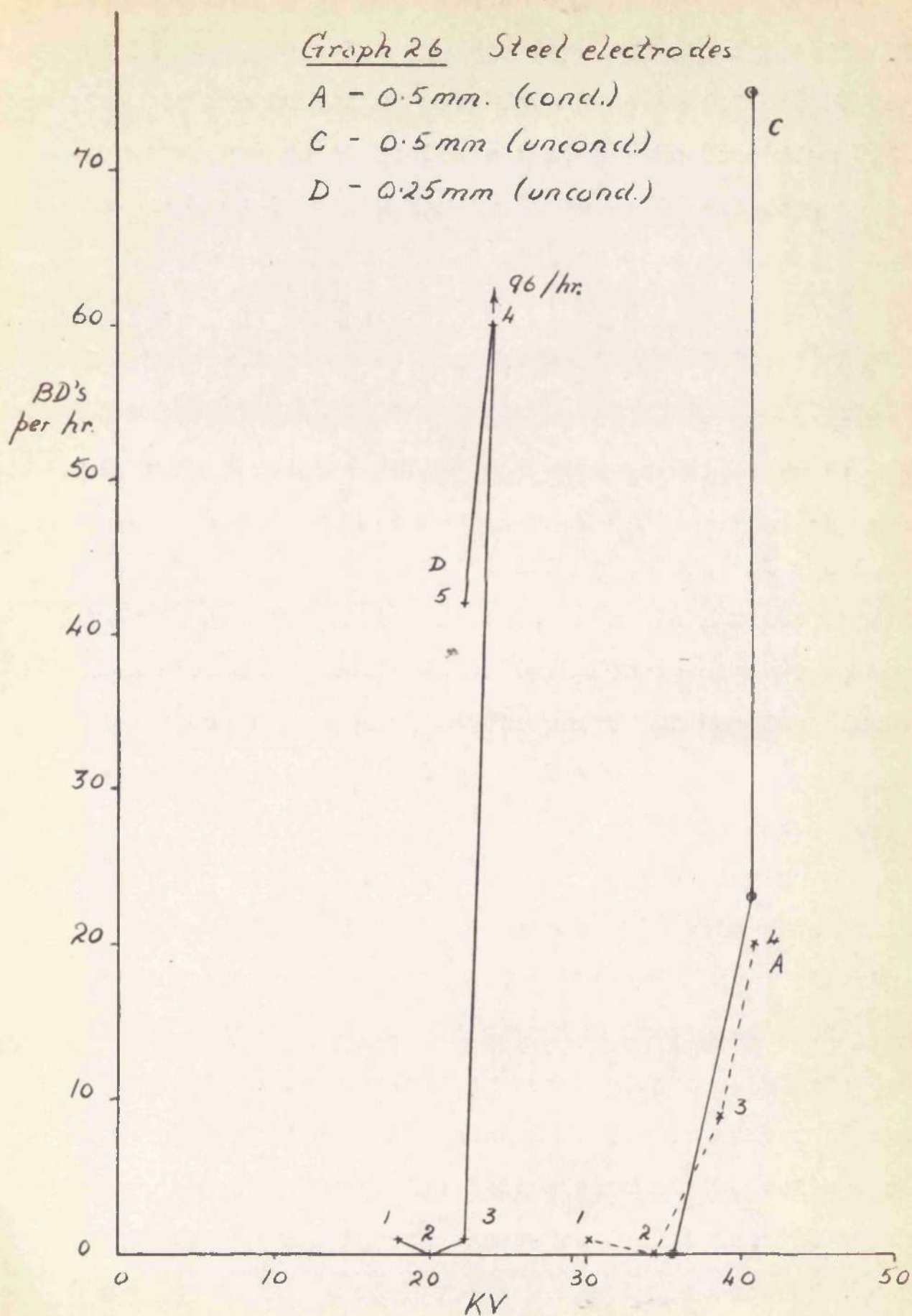


Table 12 gives, for various tests on steel, the highest voltage which gave no breakdowns in the hour, and the voltage above this which gave the first breakdown. The mean of these two figures is given as the "no breakdown value". On a few occasions a spark occurred at a voltage below that which subsequently gave no breakdowns in one hour. (see graph 26, curves A & D, points 1 & 2.) This spark was neglected and considered as merely a form of conditioning - a removal of loose, or semi-loose, material.

Tables 13 and 14 contain the corresponding figures for copper and aluminium. Graph 27 shows the mean insulation strengths obtained for the three metals tested.

Aluminium was a troublesome material due to the difficulty in obtaining a consistent surface. The steel and copper electrodes could be satisfactorily and consistently finished on a polishing buff, but this method was not suitable for aluminium due to its softness. The most consistent finish was obtained by polishing slowly on a lathe with smoothed 3/0 emery paper. The metal was obtained bright and the results on table 14 are for the electrodes finished in this way.

TABLE 12 - INSULATION STRENGTH: STEEL ELECTRODES.

Gap. mm.	No. B.D. KV.	1st B.D. KV.	No B.D. Value KV.
0.25	20	22	21
0.25	20	22	21
0.25	24	26	25
0.25	20	22	21
0.5	34.5	38.6	36.5
0.5	34.5	38.6	36.5
0.5	34.5	38.6	36.5
0.5	35.5	40.7	38.1
0.5	35.5	40.7	38.1
0.8	45.9	51.0	48.4
0.8	49.0	52.0	50.5
0.8	51.0	52.0	51.5
0.8	45.9	49.0	47.4

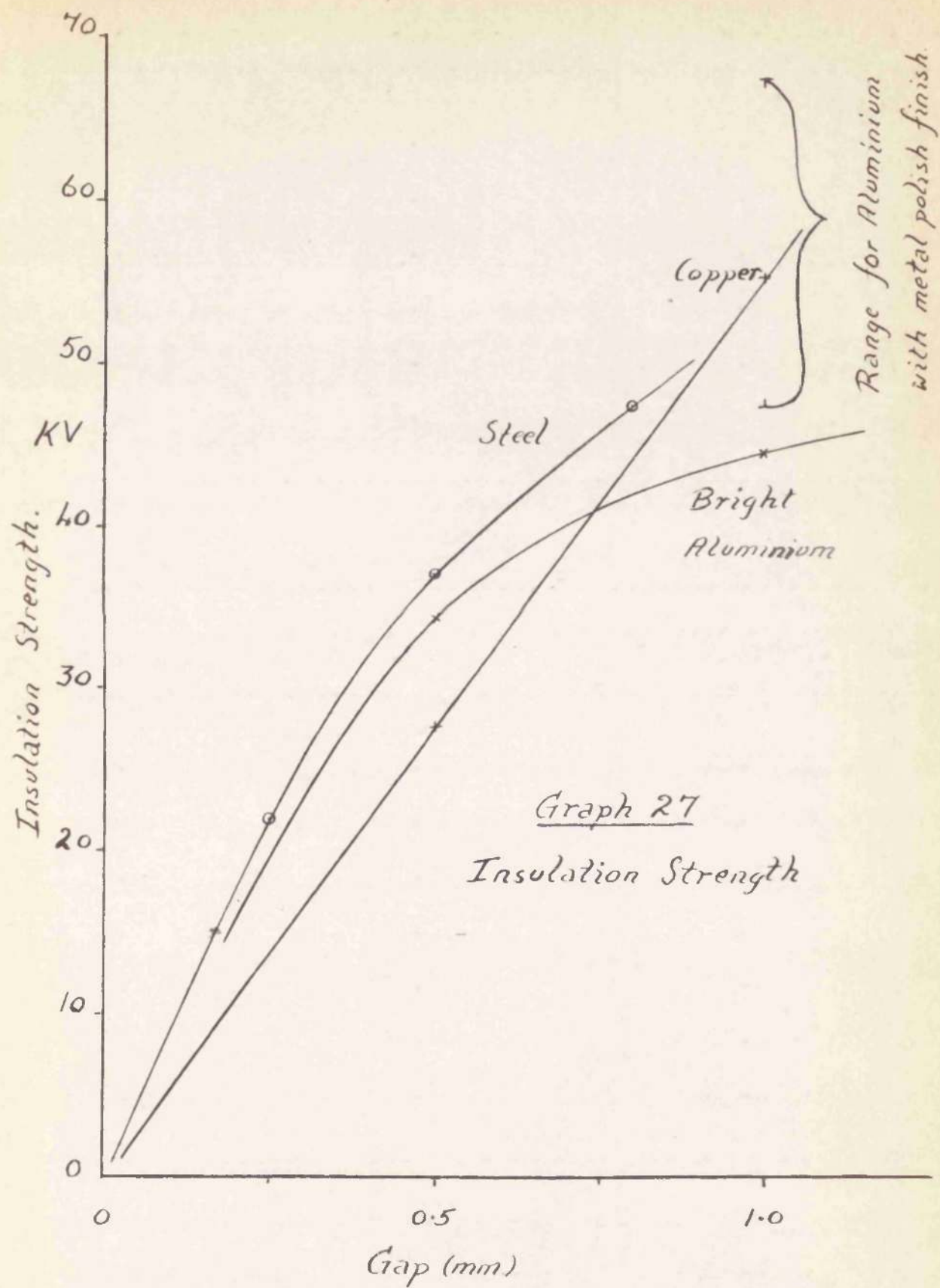
TABLE 13 - INSULATION STRENGTH: COPPER ELECTRODES.

Gap. mm.	No B.D.(KV.)	1st B.D.(KV.)	No B.D. Value (KV.)
0.5	25.2	30.3	27.7
0.5	25.2	30.3	27.7
0.5	25.2	30.3	27.7
1.0	56.1	61.3	58.7
1.0	51.0	56.1	53.5
1.0	51.0	56.1	53.5

TABLE 14 - INSULATION STRENGTH: BRIGHT ALUMINIUM ELECTRODES.

Gap. mm.	No B.D.(KV)	1st B.D.(KV.)	No B.D. Value (KV.)
0.5	32.4	36.6	34.5
0.5	32.4	35.6	34.0
0.5	32.4	36.6	34.5
1.0	46.0	49.0	47.5
1.0	40.7	42.9	41.8
1.0	40.7	44.0	42.3
1.0	46.0	48.5	47.2

Much higher breakdown voltages were obtained if the aluminium electrodes were finished using liquid metal polish instead of 3/0 emery paper. This made the electrodes smoother, but duller, and a skin seemed to be formed on the surface.



The results obtained after this type of finish were higher than with the other, but rather inconsistent. (table 14b). When the aluminium electrodes were finished with 3/0 emery paper it was usually found that the first breakdown voltage was the highest voltage that the gap would withstand - the subsequent breakdowns occurring at lower voltages. With the metal polish finish however, curves of breakdown rate to voltage were obtained for the two tests having the lowest breakdown voltages. (table 14b, A & B).

The above mentioned phenomena were probably due to aluminium oxide on the electrode surfaces. Those electrodes which were metal polish finished had probably a tough skin of oxide - the various thicknesses perhaps accounting for the high, but inconsistent, breakdown voltage. (The electrodes in these tests were not conditioned by hydrogen discharge (see page 69), and if they had been, the hydrogen would not have reduced the aluminium oxide). When the metal polish was tested subsequently, it was found to contain an alkali salt which would react with the aluminium to give the oxide.

TABLE 14b- INSULATION STRENGTH: ALUMINIUM WITH METAL POLISH FINISH.

Gap.mm.		No B.D.(KV)	1st B.D.(KV)	No B.D. Value (KV.)
A	1.0	50	55	52.5
B	1.0	45	50	47.5
	1.0	60	62	61
	1.0	65	70	67.5

4. 4. Oscillographic Studies of Spark Breakdown:

Steel, Copper and Aluminium.

Oscillographic studies of the spark current were made using the circuit shown on figure 10 with a Southern Instruments transient recorder (T.R. 10). The oscillograph time base was triggered by the voltage to be recorded which was then delayed by passing through a matched delay cable.

A study was made of the spark current for different gaps and series resistance (R_s) for steel electrodes. Plate 10 shows a typical oscillogram with a small resistance in series with the gap. The current can be considered in two parts -

(a) Initially, the capacitance to earth of the high voltage electrode and connections discharged setting up a high frequency oscillation with the circuit inductance.

(b) The capacitance C discharged through R_s and the gap.

Process (a) was seen (plate 11) to last approximately 0.1 micro-seconds. The spark current is taken to be that of process (b) which was governed primarily by the circuit constants C and R_s . The arc extinguished at about 0.5 amperes, which is called the chopping value, and if the series resistance (R_s) was increased to a value such that the maximum current available from condenser C was of the order of the chopping values, or less, the breakdown current consisted only of the discharge of the gap capacitance (process (a) - plate 12). Occasionally several such 'suppressed' breakdowns were obtained on the one oscillogram (plate 13).

Tables 15, 16 and 17 give (for steel, copper, and aluminium respectively) the peak currents and chopping values with 11K Ω series resistance and various gap settings. The mean chopping

currents for the three metals are presented on table 18.

The tables 15, 16 and 17 show a wide variation in chopping current for each metal and spacing, and table 18 shows that the mean chopping current does not vary consistently with the gap setting. This indicates that the arc extinguished at a current value which was probably more dependent on the microscopic geometry and surface condition at the emitting point, or points, than on the gap spacing. The figures for steel (table 18) indicate a larger chopping current at the smaller spacings. Comparing the mean chopping currents for the three metals at 0.5mm. spacing, it is seen that the values for steel and aluminium are similar, and less than half that for copper.

The vacuum arc occurs in the metal vapour which is produced by the bombardment of the cathode by positive ions from the arc. (58, 59). The mean extinguishing currents here, for copper, are about 50% larger than the minimum arc current given by Holm (59) (0.43 amp.) for a normal atmosphere. No figures have been obtained for the minimum arcing current for steel and aluminium, but the values for iron (.35 - .55 ampere) and carbon (0.01 ampere) would lead one to expect a lower minimum current for steel than for copper. Holm (59) also mentioned that a minimum arcing current of 12 amperes could readily be obtained with well outgassed copper electrodes in a vacuum better than 10^{-6} mm. of mercury. The electrodes in the tests described here were not outgassed and at a pressure less than 10^{-5} mm. of mercury.

TABLE 15 - STEEL ELECTRODES, OSCILLOGRAM MEASUREMENTS.

Gap. mm.	0.5	0.5	0.5	0.5	0.5	0.5	0.5
B.D.V. (KV.)	46.5	45.5	46.5	47.5	48.5	47.5	49.5
\hat{i} (amp.)	3.64	3.71	3.64	3.78	3.84	4.26	4.31
Chop current (amp.)	0.24	0.29	0.24	0.29	0.53	-	-
Time to Chop. (μ sec.)	16	16	17.5	16	12.5	-	-
Gap. mm.	0.2	0.2	0.2	0.2	0.2	0.2	0.2
B.D.V. (KV.)	27.3	25.3	26.3	25.3	25.3	26.3	25.3
\hat{i} (amp.)	2.23	2.07	2.07	2.05	2.01	2.08	2.11
Chop current (amp.)	0.81	0.24	0.52	0.52	0.19	0.86	0.52
Time to Chop (μ sec.)	6.25	14.5	7.5	8.75	15.0	6.25	10.0
Gap. mm.	0.3	0.3	0.3	0.3	0.3	0.3	0.3
B.D.V. (KV.)	31.3	32.3	33.3	35.3	32.3	34.3	35.3
\hat{i} (amp.)	2.76	2.63	2.80	2.92	2.62	3.1	3.16
Chop current (amp.)	0.19	0.67	1.30	0.29	0.14	-	-
Time to Chop (μ sec.)	16.0	10.0	10.0	15.0	17.5	-	-
Gap. mm.	0.2	0.2	0.2	0.2	0.2	0.2	0.2
B.D.V. (KV.)	27.3	25.3	26.3	25.3	25.3	25.3	25.3
\hat{i} (amp.)	2.23	2.07	2.07	2.05	2.01	2.08	2.11
Chop current (amp.)	0.81	0.24	0.52	0.52	0.19	0.86	0.52
Time to Chop (μ sec.)	6.25	14.5	7.5	8.75	15.0	6.25	10.0
Gap. mm.	0.3	0.3	0.3	0.3	0.3	0.3	0.3
B.D.V. (KV.)	31.3	32.3	33.3	35.3	32.3	34.3	35.3
\hat{i} (amp.)	2.76	2.63	2.80	2.92	2.62	3.1	3.16
Chop current (amp.)	0.19	0.67	1.30	0.29	0.14	-	-
Time to Chop (μ sec.)	16.0	10.0	10.0	15.0	17.5	-	-

TABLE 17- ALUMINIUM ELECTRODES, OSCILLOGRAM MEASUREMENTS.

Gap.mm.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
B.D.V. (KV)	48.0	46.5	51.5	55.0	48.4	56.0	54.0	56.6	53.0	49.0	54.5	61.2	58	56	62.3				
\hat{I} (amp.)	3.45	3.88	3.93	4.26	4.28	4.17	4.80	4.32	4.37	4.24	4.80	5.17	4.93	4.37	4.73				
Chop current (amp.)	0.50	0.17	0.32	0.29	0.32	0.22	0.36	0.29	0.50	0.36	0.43	0.22	0.29	0.72	0.29				
Time to Chop (μ sec.)	14	19	16	19	16	19	17	20	14	16	15	20	18	12.5	18				
Gap.mm.	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
B.D.V. (KV)	36.6	35.6	37.6	37.6	33.5	39.6	33.5	35.6	30.0	33.5	31.5	31.0	29.5	33.5	33.5				
\hat{I} (amp.)	3.1	3.08	3.17	3.17	2.84	3.28	2.89	3.10	3.59	2.86	2.81	2.66	2.56	2.84	2.84				
Chop current (amp.)	0.29	0.22	0.14	0.17	0.22	0.22	0.50	0.29	0.22	0.25	0.58	0.32	0.36	0.22	0.32				
Time to Chop (μ sec.)	14	15.5	19.0	17.5	17.0	18.0	11.5	15.0	15.0	15.0	10.0	13.0	11.5	16.0	12.5				

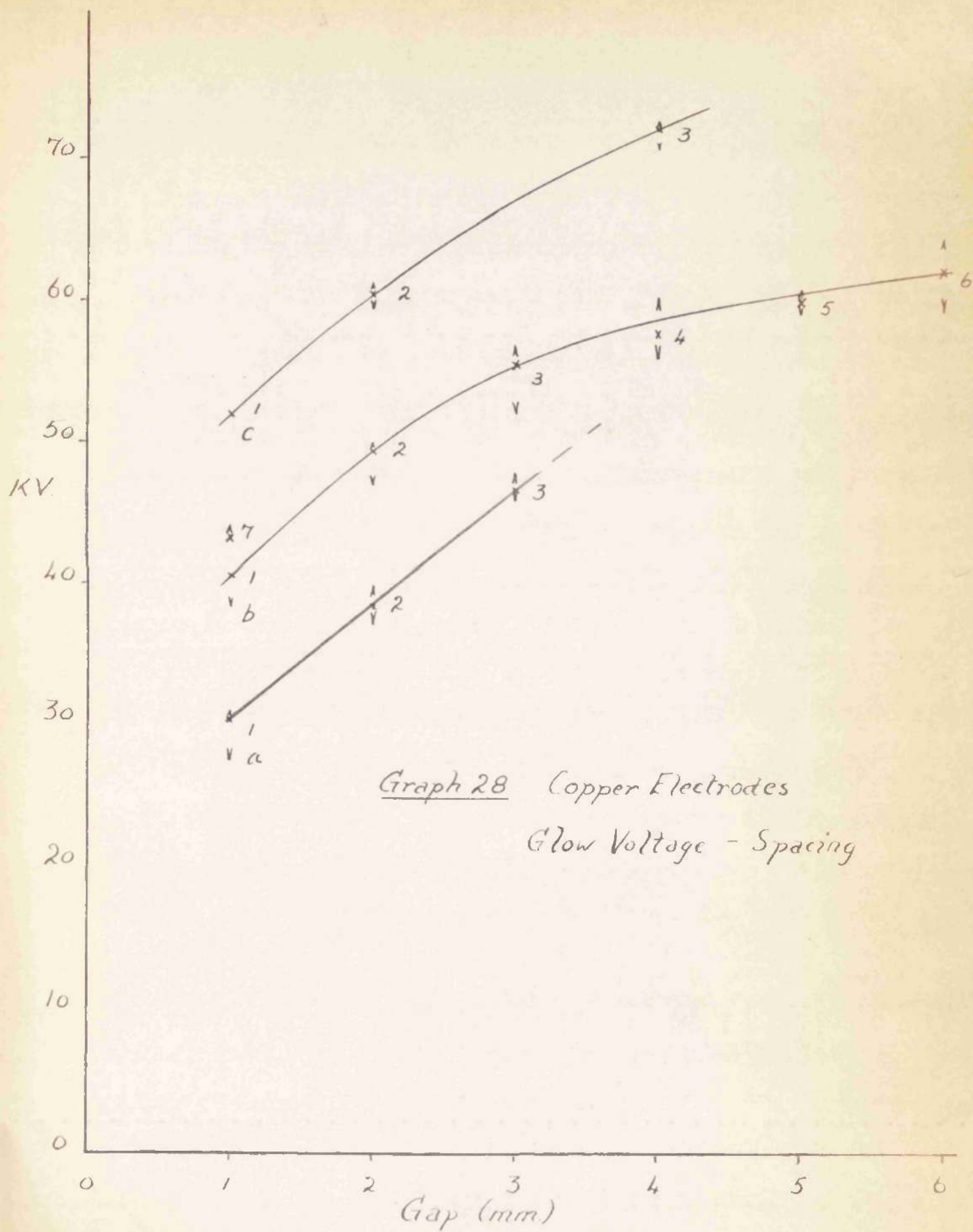
TABLE 18 - MEAN CHOPPING CURRENTS.

Metal.	Gap. (mm.)	No. of Measurements.	Mean Chop Current (amp.)
Steel	0.2	10	0.51
"	0.3	5	0.52
"	0.5	5	0.32
"	0.5	10	0.31
Copper	0.5	12	0.74
"	1.0	14	0.67
Aluminium	0.5	15	0.29
"	1.0	15	0.35

4. 5. The Glow Voltage and Oscillographic Studies of the
Glow Breakdown: Copper.

The glow phenomenon experienced on d.c. tests was similar to that on a.c. tests with respect to the visible indications (plate 5), glow voltage, and current values. Graph 28 shows three curves of glow voltage to gap spacing obtained in the order indicated. Curve (a) was started with the electrodes unconditioned and at a pressure of 7×10^{-6} mm. of Hg., which was the approximate pressure in all the d.c. experiments. The points on the curves were taken in sequence as numbered, and the spread of results for each is indicated at the particular point. It has been suggested previously that this phenomenon was attributable to adsorbed layers which can apparently be wholly, or partially, removed by the glow breakdown itself to give a higher glow voltage. After the results of point 3 on curve (a) were taken the glow voltage at 3 mm. was raised by successive glow breakdowns to 50KV. The results of curves (a), (b), and (c) were obtained on successive days. The maintained pressure in the system in each case rose to approximately 0.5 mm. of Hg. Before starting the test represented by curve (c) the glow voltage at a gap of 1 mm. was raised from 45 KV. to 52 KV.

The form of the curve of glow voltage to electrode spacing is similar to that obtained from the a.c. experiments (graph 18), rising quite rapidly from 1 to 3 mm. gap then flattening off. Comparing graphs 18 and 28b it is seen that although the general form is the same, the glow voltage given by curve 28b is higher for the intermediate electrode spacings. The discharge



circuitry was similar for both cases, and the number of glow breakdowns for each gap setting was approximately the same. In the d.c. case (curve 28b) there was better baffling between the diffusion pump and the high vacuum chamber, and it seems probable that the difference in the two curves was due to readsorption of pump vapour. This is in agreement with the findings of section 3.3.2. The readsorption phenomenon would be emphasised on a.c. if one particular polarity of electrode influenced the glow voltage more than the other since each electrode would be positive and negative in turn.

It is seen how the glow voltage can readily be raised by glow conditioning and the oscillographic study which followed was made with the object of determining the variation of glow current with gap spacing, series resistance, and thickness of adsorbed gas or vapour.

The oscillographic study of glow breakdowns was made using the circuit shown on figure 11. The only significant difference between this and the previous circuit (fig. 8) was the elimination of the 10 Megohm resistor at point A. This gave a larger discharge capacitance (approx. $0.01\mu f$) and more stable results. As the current pulse was much slower than in the spark breakdown case, the delay cable was dispensed with and a Cossor oscillograph used. Plate 14a shows a typical oscillogram of the current. The peak value and duration of the pulse were taken to be its main characteristics, and table 19 gives the measurements on two typical tests. Table 20 gives a summary of the oscillograph tests at the two gap settings and with various values of series resistance and glow voltage. Different values of glow voltage

at the same electrode spacing is taken to indicate, on the basis of the earlier premise (page 58), different 'thicknesses' of adsorbed gas or vapour. The glow voltage at a given spacing was raised when desired by causing a considerable number of glow breakdowns. (see page 80). The series resistance in this case is the sum of R_s and R_c . (fig. 11).

The effect of the various parameters on the glow current will be considered separately, using the figures on table 20.

(a) The Effect of Gap Spacing (Table 20, B. & E.)

The effect of gap spacing on the pulse amplitude and duration for similar glow voltage and series resistance is seen to be negligible.

(b) The Effect of Glow Voltage (Adsorbed Thickness Table 20, C. & E.)

The effect of adsorbed thickness for similar gap spacings and series resistance is negligible over the range tested.

(c) The Effect of Series Resistance (Table 20, D. & E.)

An increase of about 15 times in the series resistance decreased the glow current to approximately one third and almost doubled the duration of the pulse. This effect would seem to be due to the voltage sensitivity of the glow at any particular 'thickness' of adsorbed gas or vapour. When the glow occurs, the voltage across the gap will fall because of the potential drop in the series resistance and the decrease in the voltage across the condensers (C_1 and $C.$, fig. 11) due to the loss of charge. The amplitude of the glow current is in this way limited mainly by the series resistance, and since the consequent rate of loss of charge from the condenser is less for the larger

resistance, the pulse lasts longer.

Copper was the only metal of the three tested which gave consistent glow phenomena, but on rare occasions glow phenomena were seen with both steel and aluminium at large gaps (5 - 6mm.) and high voltages (60-70KV.).

TABLE 19 - GLOW CURRENT.

Gap Setting - 2mm.

Series Resistance	Glow Voltage (KV.)	Peak Current i m. amp.	Pulse Dur ⁿ . t m. sec.
9.15 K Ω	65.5	2.2	3.75
"	66.0	5.6	3.5
"	66.5	4.3	3.0
"	67.0	5.2	3.75
"	67.0	3.9	3.25
"	68.0	4.3	4.0
"	68.5	4.3	4.25
"	68.5	3.9	3.95
"	69.5	4.7	3.75
"	69.0	4.3	2.5
139K Ω	68	1.3	5.0
"	68	1.5	5.5
"	68	1.3	5.5
"	69	1.4	7.0
"	69	1.4	6.0
"	69	1.3	6.25
"	69	1.3	6.25
"	69	1.2	6.75
"	69.5	1.4	6.75
"	69.5	1.4	6.25

TABLE 20 - MEAN GLOW CURRENT.

Index Letter	Gap mm.	Series Resistance	Mean Glow (KV) Volt.	Mean Peak Current m. amp.	Mean dur ⁿ . m.sec.
A	2	159K Ω	59	1.06	6.00
B	4	159K Ω	70	1.25	7.5
C	2	159K Ω	58	1.3	7.1
D	2	9.15K Ω	67.5	4.3	3.5
E	2	139K Ω	68.8	1.3	6.1

4. 6. The Glow and Spark with Mixed Electrodes.

Experiments were carried out with mixed electrode metals of copper and steel. The electrodes were resurfaced between each of the four tests which are summarised on Table 21. There was no conditioning; the possibility of metal transfer during the hydrogen discharge was thus prevented. In each of the tests the gap voltage was raised to 70KV., or the maximum possible, and any phenomena which occurred was noted.

Table 21 shows that the glow phenomenon was obtained whether the copper electrode was the anode or the cathode. Glow breakdown was obtained in three of the four tests but it was most inconsistent. The voltage in the fourth was limited by sparking, which would tend to condition the electrodes to a high glow breakdown voltage. With a copper anode and cathode the glows started to occur at approximately the same voltage, and the glow voltage then increased slowly with successive breakdowns. With mixed electrodes the conditioning process is seen to have been very rapid. From these considerations it would appear that both the anode and the cathode contribute to the consistent glow experienced with copper electrodes.

The observations regarding the sparking voltage (Table 21), together with the fact that copper electrodes have a much lower breakdown voltage than steel electrodes (graph 22), indicate that the anode material has the more influence on the value of the sparking voltage.

TABLE 21 - MIXED ELECTRODES.

(Tests with Mixed Electrodes, Copper and Steel, 1 mm. gap.)

Phenomena seen when gap voltage raised to 70KV.)

	Anode	Cathode	Spark Phen.	Glow Phen.
F	Steel	Copper	1 at 55KV. then gap withstood to 70KV.	1 at 53 KV. (faint)
G	Copper	Steel	B.D. at 35, 39, 50 - then would withstand 50KV with electrodes very rough.	Glow at 40, 44, 49 (all faint), (voltage limited by sparking to 50KV.)
H	Steel	Copper	B.D. at 52, 55, 59, 56, 65, 65 then withstood 70KV.	Glow at 62.5, 68 (both faint.)
J	Copper	Steel	Apparent plateau reached after 12 B.D.'s. Max. B.D.V. 65.5 KV.	None visible up to 65.5 KV. (limited by sparking)

5. Conclusions.

5. 1. General.

It has been shown that hydrogen discharge conditioning can be satisfactorily used in systems which are evacuated by oil diffusion pumps, and suitable values of the discharge current density have been determined for the three metals tested. (steel - 0.25 amperes/cm.², copper - 0.125 amperes/cm.², aluminium - 0.06 amperes/cm.²). A ring of sputtered metal was formed when a discharge current of 1 ampere (0.25 amperes/cm.²) was used with copper electrodes. Guntherschultz (64) gives the following figures for the sputtered mass in micrograms per ampere-second in hydrogen. Aluminium 8, iron 19, copper 84, - steel is not given. In the experiments described here in which aluminium electrodes were used, the discharge current was limited by melting of the surfaces. (Melting point of aluminium - 660°C). The tests in which induction heating 'conditioning' was employed demonstrated the certainty of the Apiezon pump vapour cracking on the red hot electrodes, and emphasised the necessity of a cold trap when such methods of conditioning are being used with oil vapour pumps. This form of outgassing was not tried subsequently when the cold trap had been fitted, as satisfactory conditioning had already been obtained in a simpler way by running a hydrogen discharge.

The d.c. experiments with various values of series resistance showed the criterion for complete breakdown to be that the series resistance should be small enough to permit a current

of about 0.4 ampere to flow from the supply circuit. If a larger resistance was used, the gap capacitance discharged at breakdown but there was no 'follow' current from the supply. This bears out the experiments of Gleichauf and Leader and adds considerably to the information they presented. Electrodes of steel, copper and aluminium were used and the value of current at which the arc extinguished for different gaps was determined. These results indicated that the 'chopping' current depended more on the microscopic geometry at the spark root on the cathode than on the gap spacing.

Leader found that his spark current under impulse conditions extinguished at about 0.25 ampere. If his series resistance was large enough to prevent this value of current from flowing, the spark current consisted only of the discharge of the gap capacitance which could be repeated (see plate 13 - suppressed discharges under d.c. conditions). As suggested by Leader, the series resistance effect does take place under d.c. conditions, and it seems probable that this phenomenon can account for some of the differing information which has been published on high vacuum breakdown. If a galvanometer was used as a means of indicating breakdown in a test with high series resistance, it would read the integrated current of a succession of incomplete breakdowns. It is more likely that the surface roughness, which has here been shown to occur when the breakdown is suppressed (plates 3 and 4), accounts for the widely varying results obtained by some previous investigators. By using a high resistance in series with the gap during a breakdown run,

a plateau can be attained in the voltage readings which is considerably below that attained when the series resistance is negligible. Graph 17 gives two curves of breakdown voltage - gap spacing for the same metal but different series resistance. The d.c. experiments which determined the spark extinction current (approx. 0.4 ampere) agreed with the a.c. series resistance experiments. The a.c. tests with a resistance of 100K Ω (peak discharge current 0.5 ampere, assuming a breakdown voltage of 50KV) or more, had large standard deviations or low breakdown voltages (tables 5 and 7). Those experiments with 50K Ω in series with the gap (1.00 amp.) had comparatively small standard deviations, but the maximum breakdown voltages were rather low (table 5). Unfortunately in some of the published work the circuit elements are not specified, and this lack of detail is also common in the presentation of breakdown voltage figures - no mention is made of whether the value given is the maximum attained, the mean, or the voltage which could be withstood over a long period. Few references contain information as regards the consistency of the results.

In cases of small interelectrode capacitance and high series resistance it seems conceivable that phenomena such as a luminous particle flying from cathode to anode (11, 14, 78) should be seen rather than a spark bridging the gap. Bennet, (19) who used a series resistance of 10 M Ω , mentions in accordance with the findings here (page 53) that breakdown produced subsequent high field emission, but Anderson (32) stated that sparking with a more powerful source than his electrostatic

generator gave serious roughening. No mention is made however of the resistance in series with the source.

The present work, which has shown the effect of breakdown occurring when there is large series resistance, suggests that in equipment where such conditions exist and failure is being experienced, the trouble may be removed by sparking with a high voltage circuit having a low series impedance.

Consistent spark breakdown voltages have been obtained for steel, copper and aluminium electrodes under a.c. conditions and corresponding experiments under d.c. conditions showed the importance of the rate of rise of voltage, i.e. the time effect. The highest rate of increase of voltage was during the a.c. tests (zero to maximum voltage in $\frac{1}{4}$ cycle, 5×10^{-3} second). This will be discussed later in section 5.3. The experiments which were influenced least by the time effect were those with the highest rate of rise of applied voltage, and consequently the figures obtained during the a.c. tests have been used when considering the breakdown mechanism. These tests have shown standard deviations of the order of 4% (table 5) under the best conditions, and there is consequently an appreciable difference between the maximum and the average breakdown voltage in a test. This scatter in the results was due to a change in the state of either the anode or the cathode surface caused by successive breakdowns. The experiments, in particular those showing the effect of high series resistance and the consequent surface roughening, indicate that it is the change in the surface geometry at the point on the cathode where breakdown occurs,

which is the predominant cause of the deviation. From such considerations, it follows that the maximum breakdown voltage would be obtained when the cathode roughening was at a minimum. That is, the microscopic surface gradient at the cathode was nearest the average gradient when the breakdown voltage was at its maximum. For this reason it is the maximum alternating breakdown voltages which have been considered in the discussion on the discharge mechanism.

The maximum alternating breakdown voltage obtained at gaps of 1mm. (the figure for steel by extrapolation on graph 29) is given here along with the results of previous investigators.

1mm. gap	Copper	Aluminium	Steel
Denholm (a.c. 6KV/sec.)	68.5 KV	78 KV	95 KV
Anderson (32)	37 KV	41 KV	122 KV
Trump & Van de Graaf (39)	-	-	110 KV

The experiments described here have shown the importance of the rate of rise of voltage. The figures given by Anderson and Trump et al were obtained using d.c. and the rate of rise of voltage is not given. The author's figures given above were obtained with Apiezon vapour present and the test with the cold trap gave an increase in the breakdown voltage of 8%. The figure given by Leader (48) for the impulse breakdown voltage between steel spheres at a gap of 0.3mm. was 14 KV. This compares with 48 KV (a.c.) and 38 KV (d.c., 6 KV/second) obtained in the present experiments. From the effect of time of duration of voltage a higher impulse breakdown value would be expected. There has never, as far as is known, been any suggested reason why the breakdown voltage in high vacuum under impulse

conditions should be lower than that under d.c. conditions, and it seems possible that Leader's results were confused by surface roughness.

The present experiments indicate that steel is the best material to use for the prevention of high vacuum breakdown. Aluminium electrodes can have a higher insulating strength (i.e. with respect to the effect of duration of voltage - graph 27) but they are more readily damaged by a breakdown when it occurs. This is in accordance with the findings of McKibben and Beauchamp (page 24) and is almost certainly due to a tough skin of aluminium oxide which forms on the electrodes, giving a higher breakdown voltage than for pure aluminium. When a spark occurs in high vacuum and the soft aluminium is exposed, the subsequent breakdowns are at a much lower voltage. From the work of Llewellyn Jones and de la Perelle (65) on electrodes coated with oxide, it might be expected that the presence of oxide would decrease the breakdown voltage. Their work showed that electrons could be drawn from the oxide coating at much lower field strengths than from the pure metal, and they proposed that the initiatory electrons for the impulse spark in air came from this source. It has been suggested here that breakdown in high vacuum occurs at the higher voltages due to the 'clump' mechanism (Cranberg) and at the lower voltages (and higher cathode field strengths) due to the high current density on a projection. It is quite feasible that an increased electron emission general to the whole cathode surface would have little effect on either of the above processes. It has been shown by other investigators

(66) that the presence of oxide on aluminium decreases very considerably the rate of sputtering caused by bombardment by positive ions, and it is thought that the increase of breakdown voltage in high vacuum due to aluminium oxide is probably due to similar reasons.

The values of breakdown voltage obtained here during the a.c. experiments and those obtained by previous investigators (apart, perhaps, from Tomaschewsky) can not be satisfactorily used in the design of equipment without further information on the effect of time of application of voltage. The results obtained from the d.c. tests and given on graph 27 (Insulation Strength) are suitable for design purposes. Such information has not, as far as is known, been previously obtained. Tomaschewsky gave a figure of 40KV/mm. as the average gradient which a high vacuum gap could withstand without rigorous conditioning. He obtained this figure from experiments at 1 mm. and 3.5 mm. gaps with electrodes of various geometries and materials and with some outgassing (see page 5). The curves (graph 27) show that to give one average breakdown gradient for the high vacuum gap, irrespective of electrode spacing or material, is not satisfactory. The average gradients which the steel electrodes could withstand at gaps of 0.25 mm. and 1 mm. were 88 KV/mm. and 53.5 KV/mm. These figures were obtained without conditioning. The experiments of Tomaschewsky do not seem to be mentioned in the English literature on high vacuum breakdown.

The maximum breakdown voltage figures obtained on a.c. indicated the advantages of preconditioning with a hydrogen discharge for obtaining curves of maximum values. However, the

results of the d.c. rate of sparking experiments showed that as far as the permanent insulating strength of the gap was concerned there was nothing to be gained by this method of conditioning. In fact, the consistency and comparatively high value of the results with the unconditioned electrodes are rather surprising.

The tests showed that a factor of safety was desirable when applying the values given on graph 27. The lowest "No B.D. Value" at each gap (tables 12, 13 and 14) was taken as a percentage of the insulation strength at that gap (graph 27) and the lowest value obtained was 93.5%. However, to allow for the 'conditioning' spark which occurred in an occasional test (see page 70) a factor lower than this is necessary. A consideration of the results obtained during all the tests indicated that 75% would be a safe factor.

The glow phenomena described and studied here (sections 3.3.2. and 4.5.) has not as far as is known been previously reported, although it seems similar in some respects to the current loading sometimes experienced in accelerator tubes and to the form of conduction described by Clifford, Fortescue and Roberts (60).

Turner (61) and Blewett (62) described a current loading phenomena which occurred in high voltage accelerator tubes. The outstanding characteristics were

(a) the discharge starts at a definite voltage as evidenced by the sudden appearance of X-rays and increased current drain,

(b) the discharge current increases approximately with the sixth power of the voltage and hence is an effective voltage limiter,

(c) the voltage at which the discharge occurs depends on the pressure, increasing with tube pressure,

(d) hydrogen, helium, nitrogen, and argon affect the threshold voltage in approximate relation to the mass of gas present. Blewett considered the effect to be associated with surface layers of reasonably volatile materials, probably pump oils or other organic vapour. He was able to reproduce the phenomena at voltages from 2-30KV in a 'parallel plane diode' with the electrodes 1 mm. apart. This represented average gradients of the order of tens of KV per cm. which corresponds to the surface gradients at the electrodes of conventional Van de Graaf accelerator tubes. The onset of the effect was found to depend on field strength, not total voltage, and to be strongly affected by surface contaminations.

McKibben and Boyer (63) showed that the electron loading phenomenon in accelerator tubes was due to a positive ion - negative ion chain reaction. They noted that the voltage at which the discharge occurred was not affected if a magnetic field was applied which prevented electrons, but not negative ions, from striking the anode.

Clifford et al (60) described a discharge of the order 10^{-4} amperes which set in at voltages from 10 - 150KV, d.c., across gaps of a few centimetres in a continuously evacuated system. The effect was dependent on the anode condition and affected little by large variations of gap. The discharge was self extinguishing after a charge of microcoulombs had crossed the gap with only a slight drop in voltage.

All the investigators just mentioned found the threshold voltage for the discharge to be considerably raised by an increase in the pressure up to the order of 10^{-4} mm. of mercury.

The present experiments with a copper anode and a steel cathode, which gave a lower spark breakdown voltage than with a steel anode and a copper cathode, showed that the material of the anode had a considerable bearing on the breakdown voltage. This agrees with the findings of most of the previous investigators.

The pressure during all the experiments described here was between 2×10^{-6} mm. of mercury and 10^{-5} mm. of mercury as read by the ion gauge. Over this range, no effect which was attributable to the degree of vacuum was noted. Previous investigators (32, 37, 39) have confirmed that this region is well below that at which the spark breakdown voltage ceases to depend on pressure. The residual gases and vapours in the vacuum chamber were probably a mixture of hydrogen, water vapour and Apiezon products. The pressure dropped to one half when the refrigerant was put in the cold trap. Blears (72) found on analysing a dynamically pumped system similar to that used here (with Apiezon oil diffusion pump and no cold trap), that, although there were traces of water vapour and hydrogen, the predominating residuals were hydrocarbon vapours from the pump.

During the experiments it was noted that the surface finish on the electrode surfaces had little effect on the breakdown voltage. There was no appreciable difference in the breakdown voltage between electrodes which were buff polished and those which were papered with fine emery.

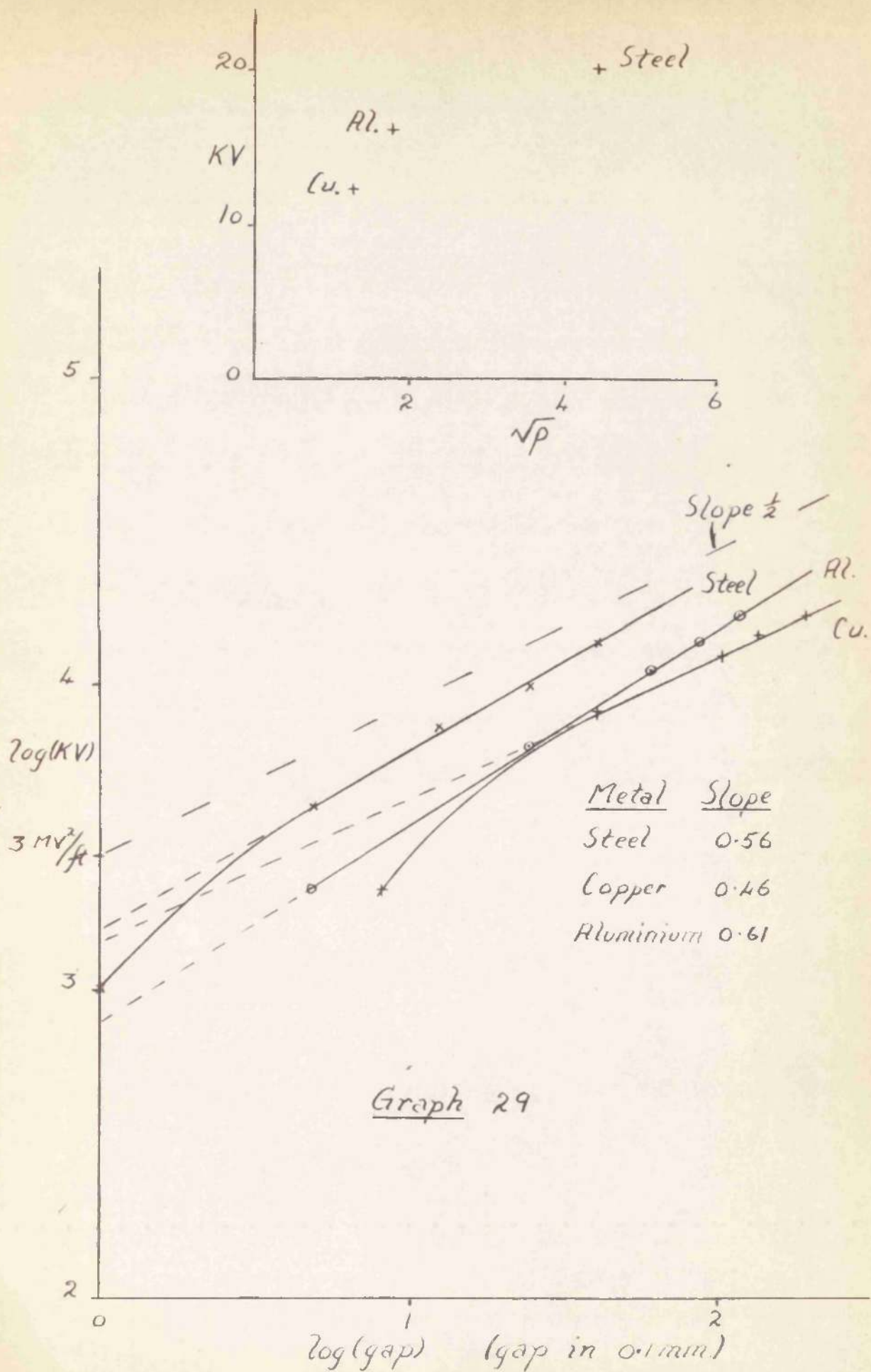
This is in accordance with the results of Hadden (71), who found that electrolytically polishing his copper electrodes did not increase the breakdown voltage.

5. 2. The Breakdown Mechanism.

Graph 29 shows a double log plot of the maximum breakdown voltage figures of graph 22 as suggested by Cranberg (47). A typical value suggested for the constant C given by the Y axis intercept was $3 \text{ MV}^2/\text{ft}$ and the line shown dotted is of slope one half through this point. The curves for copper and steel are linear for all but the smallest gap and are approximately of slope one half. The curve for aluminium is linear over the whole range with slope 0.61, and extrapolation indicates that at larger gaps this metal would be superior to steel. These curves supply strong evidence that for the larger gaps the breakdown is due to the Cranberg mechanism. This is supported by the figures on table 21 which indicate that the material of the anode plays an important part in the breakdown mechanism. This suggests that the origin of the particles is the cathode and that the target is the anode with the characteristic constant C.

The evidence of other investigators which supports this view of Cranberg's theory is -

- (a) The rotating mirror photographs of Snoddy and Beams showed that initially a luminous spot appeared at the anode and the spark bridged the gap from anode to cathode.
- (b) Compton and Langmuir mentioned bright charged particles flying from cathode to anode.



(c) The experiments which showed an anode effect (page 35).

The evidence of investigators which seems to contradict this theory is -

(a) Jin Imachi found that a projection on the anode lowered the breakdown voltage, but that one on the cathode did not.

(b) The experiments of Gleichauf and Ahearn which indicated no anode effect. (commented on previously (page 37).)

The figures for 0.1 mm. gap steel and 0.25 mm. gap copper, which are 4.5 KV. and 7 KV. respectively below the values expected from the Cranberg theory, suggest the probability of a field dependent mechanism predominating over the total voltage effect at the smallest spacings and highest gradients. It is possible, however, that the low values could still be due to the mechanism preferred by Cranberg. In the development of his theory for uniform field conditions, he assumed that the field distortion at the clump on its parent electrode was constant, and independent of the electrode spacing. If the distortion increased appreciably at the smaller spacings, breakdowns would occur at voltages below those deduced from considerations which neglected this intensification of the field.

As the gap spacing is decreased the surface gradient at a given projection on the cathode increases. There is consequently larger electron emission from the point, and it seems probable that the mechanism suggested on page 36 accounts for breakdown. This process depends on the temperature produced at the point by the high current density and by the bombardment with positive ions from the anode. It is thought that, normally, the heating

due to the current density has the major influence. The effect of positive ions from the anode can be eliminated by applying pulse voltages. Goodman and Sloan⁷⁷ experimented with high voltage microsecond pulses and found that the cathode gradient at breakdown was proportional to the square root of the specific resistance of the metal. The inset on graph 29 shows the breakdown voltages at 0.1 mm. gap (graph 22) plotted against the square root of the specific resistance of the respective metals. The breakdown voltage increases with the root of the specific resistance, but not linearly.

Trump and Van de Graaf measured the coefficient A (the number of positive ions emitted per incident electron) for steel at different voltages, and at 20 KV the value was 4×10^{-4} . Filosofo and Rostagni, who used Apiezon oil diffusion pumps, also measured this coefficient and found it less than Trump and Van de Graaf's by a factor between 200 and 2,000; but if they removed their cold trap an increase of about 200 was obtained. These figures suggest that in the former experiments the target was contaminated by organic vapours. The electrodes used in the tests here would be similarly affected. Dyke and Trolan have shown that high current densities exist on points at breakdown (order of 10^8 amp./cm.²). If the anode was bombarded by electrons from such a projection, there would be large positive ion densities produced. These ions, when accelerated through the gap voltage, could be expected to produce considerable heating at the projection, which would supplement that due to resistive heating. Even an approximate calculation of the relative effect of either of the two thermal processes would

involve a knowledge of the emitter geometry and the following mathematical considerations.

- (a) The lateral diffusion of the electron beam due to the space charge (this has been calculated in section 5.4 for the vacuum spark). Dyke and Trolan (4) found that their field emission current was being limited by space charge at current densities below those at which breakdown occurred.
- (b) The focussing of the ion beam by the electron stream. (positive ion current \ll electron current).
- (c) The heat produced at the surface of the projection by ion bombardment.
- (d) The resistive heating of the projection due to the high current density.
- (e) The rate of dissipation to the body of the metal of the heat produced by (c) and (d).

The effect of time of application of voltage would also enter into the considerations (section 5.3.)

Most of the experiments and evidence considered to determine a possible breakdown mechanism have been concerned with d.c. or low frequency studies. Dyke et al (50, 51) have shown, by applying pulses shorter than the ion or 'clump' transit time, that the breakdown can be produced by high current density alone. Kilpatrick (73) showed that sparking at 200 Mc/s. followed strictly the surface gradient and did not depend on the total voltage.

5. 3. The Time Effect.

Experiments of the type described here can not furnish definite proof of the mechanism which causes delayed breakdown at a given voltage. The microscopic geometry of the region at which the breakdown occurs is not known, and the basic figures involved in the suggested mechanism (see later) have not, as far as is known, been obtained. It is possible however to deduce what probably happens.

Although the time effect is a fairly well known phenomenon there does not seem to be any previously published results on it at the lower voltages. At the higher voltages ($>100\text{KV}$) some results have been published on the basis of the sparking rate (40). None of the investigators apart from Gossling (23) (see later) proffered an explanation for the phenomena.

The long times to breakdown which can be experienced, exclude the possibility of chain mechanisms (e.g. (c) and (d) page 34) accounting for the phenomenon which would appear to be initiated by a single event. This leaves the Cranberg theory and that postulated under (a) of page 34, both of which require an explanation for the time delay in tearing a projection from the cathode.

Consider a microscopic projection on the surface of the cathode with a high voltage across the gap. If the projection is considered as taking the form of an ellipsoidal column on a flat plane, a ratio of height to diameter of 3 to 1 would give a tenfold increase in the gradient at the apex as compared with the macroscopic gradient (67). There is -

(a) high electrical and mechanical stress at the point,

and

(b) large electron emission and thus high temperatures due to resistive heating and perhaps bombardment by positive ions from the anode.

This could lead to rupture by two processes -

(1) the temperature at the point rises and when the melting point is reached the load causes mechanical rupture.

(2) with high temperature and mechanical load failure takes place due to creep. (70). This is a phenomenon of viscous flow at grain boundaries under conditions of high temperature and stress.

It is difficult to reconcile process (1) with the long delays before breakdown which can be experienced, as an equilibrium temperature would be reached in a very short time. Process (2) on the other hand can take days or even years depending on the conditions of temperature and stress. At the normal creep testing temperatures fracture takes place after many days have elapsed but very fast creep could be expected above a red heat (800°C approx.). The effect is cumulative - the greater the extension due to creep, the greater is the mechanical force, electron emission, and temperature.

Gossling (23) proposed a similar theory although he wrote in terms of crystal slip and cited the work of Groucher (68) and Schoenborn (69). They experimented with tensile tests on single crystal wires at various temperatures and showed that

$t \propto \Sigma^6$ at constant temperature, and

$t \propto \Sigma^7$ at constant stress,

where t is the time to fracture,
 s is the mechanical stress,
and T is the temperature ($^{\circ}\text{K}$).

Times as short as seconds were obtained. This type of expression corresponds very approximately to the form of the rate of sparking curves obtained (graph 26).

If the stress on a specimen is removed after a period of creep there is a partial recovery of the extension. When alternating voltage was applied between the electrodes there would be a relaxation, during each alternate half cycle, of the stress on the projections. In such tests it can then be considered that the voltage was raised to its maximum value in a quarter of a cycle (0.005 second).

5. 4. The Dimensions of the Spark Roots.

The microphotographs have shown (plates 8 & 9) that the diameter of the spark root on the anode considerably exceeds that on the cathode. It has been suggested that this is due to mutual repulsion of the electrons in the beam. The electrons leaving the cathode will have a Maxwellian distribution of velocities and this is another possible reason for the lateral diffusion. It is likely, however, that at the comparatively high current density in the spark the space charge effect will predominate, and it will be shown that this effect alone can account for the broadening of the electron beam.

As the current in an electron beam is increased, the effect of space charge is noted as a lateral dispersion of the electrons at current densities below those which are sufficient to

appreciably change the potential along the axis of the beam. In the vacuum arc there is no conducting plasma as in the arc in air (59), and in the considerations which follow it has been treated as a high current density electron beam.

Pierce (75) developed an expression for the broadening of a paraxial electron beam under uniform field conditions by using the following assumptions.

- (a) The potential along the axis of the beam is not changed by the charge density of the electron stream.
- (b) The current density is independent of the radial position inside of the beam.
- (c) The effect of the thermal velocities of the electrons can be neglected.

Definition of the variables used by Pierce.

The z coordinate lies along the axis of the beam.

r = radius of the path, r_0 = radius at $z = 0$

$$R = \frac{r}{r_0}, \quad Z = \left(\frac{I}{2\sqrt{2}\pi\epsilon\gamma V^{\frac{3}{2}}} \right)^{\frac{1}{2}} \frac{z}{r_0} = 174 \frac{I^{\frac{1}{2}} z}{V^{\frac{3}{2}} r_0} \quad (1)$$

where, I is the current in the chosen path,

V is the voltage.

$$R' = \frac{\partial R}{\partial Z} \quad \text{and} \quad R'_0 = \frac{\partial R}{\partial Z} \quad \text{at} \quad z = 0$$

The expression developed by Pierce is

$$\begin{aligned} Z &= 2e^{-(R'_0)^2} \int_0^{R'} [\ln R + (R'_0)^2]^{\frac{1}{2}} e^{u^2} du \quad (2) \\ &= 2e^{-(R'_0)^2} \left[\int_0^{R'_0} [\ln R + (R'_0)^2]^{\frac{1}{2}} e^{u^2} du - \int_0^{R'_0} e^{u^2} du \right] \end{aligned}$$

The integral may be evaluated by using the following function (suggested by Pierce and graphed, originally, by Miller and Gordon (76).)

$$F(x) = e^{-x^2} \int_0^x e^{y^2} dy \quad (3)$$

$$\therefore Z = 2e^{-(R_0')^2} \left[e^{[L R + (R_0')^2]} F[L R + (R_0')^2] - e^{-(R_0')^2} F(R_0') \right]$$

Here $R_0' = 0$ (taking bound of the path initially normal to the cathode surface.)

From plates 8 and 9 the diameter of anode mark = 0.43 mm.

" " " cathode " = 1.15×10^{-2} mm.

$$\text{i.e. } R = \frac{r}{r_0} = \frac{0.43}{1.15 \times 10^{-2}} = 37.4.$$

$$\text{gives } Z = 24.3.$$

Oscillograms indicated that the arc voltage was of the order of 1KV. The series resistance was 100 K Ω and the breakdown voltage approximately 50KV. ($\hat{I} = \frac{50 \times 10^3}{100 \times 10^3} = 0.5$ amp.).

Substituting $Z = 24.3$, $V = 10^3$ and $I = 0.5$ in (1)

$$\text{gives } \frac{Z}{r_0} = 35.3 \text{ or } z = 0.41 \text{ mm.}$$

That is, the length of the electron beam necessary to give the stated spread due to space charge under the specified conditions of current and voltage was 0.41 mm. The actual gap length was 0.5 mm.

5. 5. The Glow Breakdown and Possible Mechanism.

The phenomena mentioned in sections 3.3.2. and 4.5. are obviously due to some form of adsorption on the electrode surfaces. From the times to equilibrium (graph 19) it is evident that the adsorption is multimolecular, since a monolayer would form in less than 0.6 second at the working pressure. (5.5×10^{-6} mm. Hg. - table 4). This form of adsorption is characteristic, in general, of vapours at pressures approaching saturation values (74, page 424). At normal temperatures in

high vacuum, residual gas (i.e. air etc.) would not be expected to form more than a monolayer on a clean metal surface. The pump vapour present would be near its saturation pressure (10^{-7} mm. Hg., or higher if cracked) and this indicates strongly that the glow phenomenon is caused by a thin film of pump vapour. Experiments showed that pump vapour had a considerable influence on the glow voltage. (section 3.3.2.)

As far as is known no investigations have been made on the rate of adsorption of Apiezons or other similarly complicated organic vapours. Bangham and Burt (74, page 452) obtained the following empirical relationship for adsorption of ammonia, carbon dioxide, sulphur dioxide, and nitrous oxide by glass surfaces.

$$\log \frac{\delta}{\delta - s} = K t^{\frac{1}{n}} \quad \text{ie.} \quad s = \delta (1 - e^{-K t^{\frac{1}{n}}})$$

where s is the amount adsorbed,

δ is the amount adsorbed at saturation,
and n , K are constants.

The quantity adsorbed increases exponentially to the saturation value (δ). This value (δ) corresponds to the equilibrium glow voltage (V_g), and zero adsorption corresponds to the sparking voltage (V_s) (graph 19). This, together with the form of the curve, suggests that an empirical relationship

$$v = V_g + e^{-\alpha t} (V_s - V_g)$$

might hold for the decay of glow voltage with time, where v is the glow voltage at time t ,

V_g is the equilibrium glow voltage,

V_s is the sparking voltage,

and α is a constant.

If this relationship applied, the curve

$$\log (v - V_g) = \log (V_s - V_g) - \alpha t$$

would be linear. It is seen (inset, graph 19) that this is so after approximately one hour's adsorption. (The deviation of point A from this line is actually only 300 volts or 0.7% of the glow voltage.) The fall of glow voltage is very rapid over the initial adsorption period.

The following phenomena require to be accounted for. The glow voltage -

- (a) falls with increase of thickness of adsorbed vapour,
- (b) requires a certain minimum voltage for initiation and depends more on the total voltage than upon the stress (graph 18),
- (c) is self extinguishing,
- (d) can be raised by successive glows,
- (e) is influenced by the state of the anode and the cathode surfaces.

The fact that details of the adsorbed vapour (e.g. formulae, ionisation coefficients) are unknown, apart from it being Apiezon, makes even approximate calculations on a probable mechanism impossible. However, a qualitative suggestion for the glow mechanism is given. Electrons from the cathode cross the gap and ionise some of the molecules of the anode film. Investigators (46) have shown that the emission of positive ions per electron from an adsorbed organic layer is much larger than that from the pure metal surface. The probability of the electron having an ionising collision with an adsorbed molecule before striking the actual metal will increase with the thickness of the

film. The positive ions produced at the anode cross the gap and give further ionisation at the cathode surface (the amount depending on the film thickness). Photoionisation will also occur at the anode and cathode surfaces due to the ionisation processes on the opposite electrodes. When there are sufficient ions and electrons in the gap, the glow phenomenon, which is similar in some respects to the normal glow discharge, results. The voltage across the gap drops only slightly when the glow occurs, and a high voltage is required to maintain the phenomenon. This corresponds to the case of the glow discharge.

The mechanism here described would account for the fact that the glow depended more on the total voltage than on the gradient (i.e. it depended on the energy acquired by the ions and electrons crossing the gap). Self extinction is apparently a consequence of the drop in gap voltage due to the circuit parameters, assisted, perhaps, by loss of vapour by diffusion from the gap. The rise in glow voltage with successive discharges is probably due to removal of some of the vapour from the gap by diffusion to the extra-gap space during the glow and immediately after it had occurred.

5. 6. Recommendations for Future Work.

The experiments described here have shown that a fair consistency in breakdown voltage can be obtained by ensuring that current from the supply 'follows' the initial discharge of the gap capacitance. Standard deviations of about 5% were obtained when a condenser of 500pf. was discharged through the gap at breakdown. (see fig. 5). Between this condenser and the

electrodes there was, effectively, the small inductance and resistance of the connecting leads (a total length of approx. 6 feet) and the two gas gaps. This appears to have had some bearing on the standard deviations in the tests. For example, graph 13 shows that 17.5 pf. added across the gap (short leads, total length approx. 18") had increased the scatter, although the nominal series resistance was zero ($R_s = 0$). If the small inductance and resistance of the leads from the 500 pf. condenser had no appreciable effect it would be unlikely that the addition of the 17.5 pf. would have made any significant difference. A closer study of the effect of the circuit parameters on the standard deviation could lead to more consistent results and further studies could follow from them. If the expected breakdown voltage was known to a reasonable accuracy, it would be possible to study closely the effect of time of duration of voltage by applying different percentages of the breakdown voltage and determining the time to breakdown.

The a.c. and d.c. tests have shown a distinct difference in the relative maximum breakdown voltages, and it would be of interest to determine the maximum breakdown voltages under impulse, which would eliminate, as far as possible, the effect of time. Impulse studies are now being carried out, and they indicate maximum breakdown voltages which are as much as 25% above those obtained in the a.c. experiments.

Further experiments with an improved high vacuum system, which would eliminate completely, when necessary, the presence of pump vapour, are desirable. This would make possible a reasonable comparison of the relative merits of conditioning by

hydrogen discharge and by induction heating, without the confusion of pump vapour cracking on the electrodes when red hot. Such an improved system would also make possible positive confirmation that the glow phenomenon is due solely to the organic vapours from the diffusion pump. The glow conduction could bear more exhaustive examination under closely controlled conditions, which would determine, in greater detail, the processes involved.

Gleichauf (43,44) has published results on high vacuum breakdown over insulators at voltages similar to those used in the present experiments, but there is still a lack of information on the subject. Useful results could be obtained by extending the techniques developed here to cover the field of breakdown over insulators in high vacuum.

6. Acknowledgment.

The author wishes to express his gratitude to Professor F.M. Bruce, M.Sc., Ph.D., M.I.E.E., A. Inst. P. for the use of the facilities of the Electrical Engineering Department of the Royal Technical College and for advice given during the course of this study. The author is deeply appreciative of the suggestions made by Mr. A.S. Husbands, B.Sc., A.M.I.E.E. and of the skilled assistance given by the technicians of the Department when building the equipment.

No small debt of gratitude is due to the Royal Technical College, The Carnegie Trust, and the Sir James Caird Trust, for generous scholarships.

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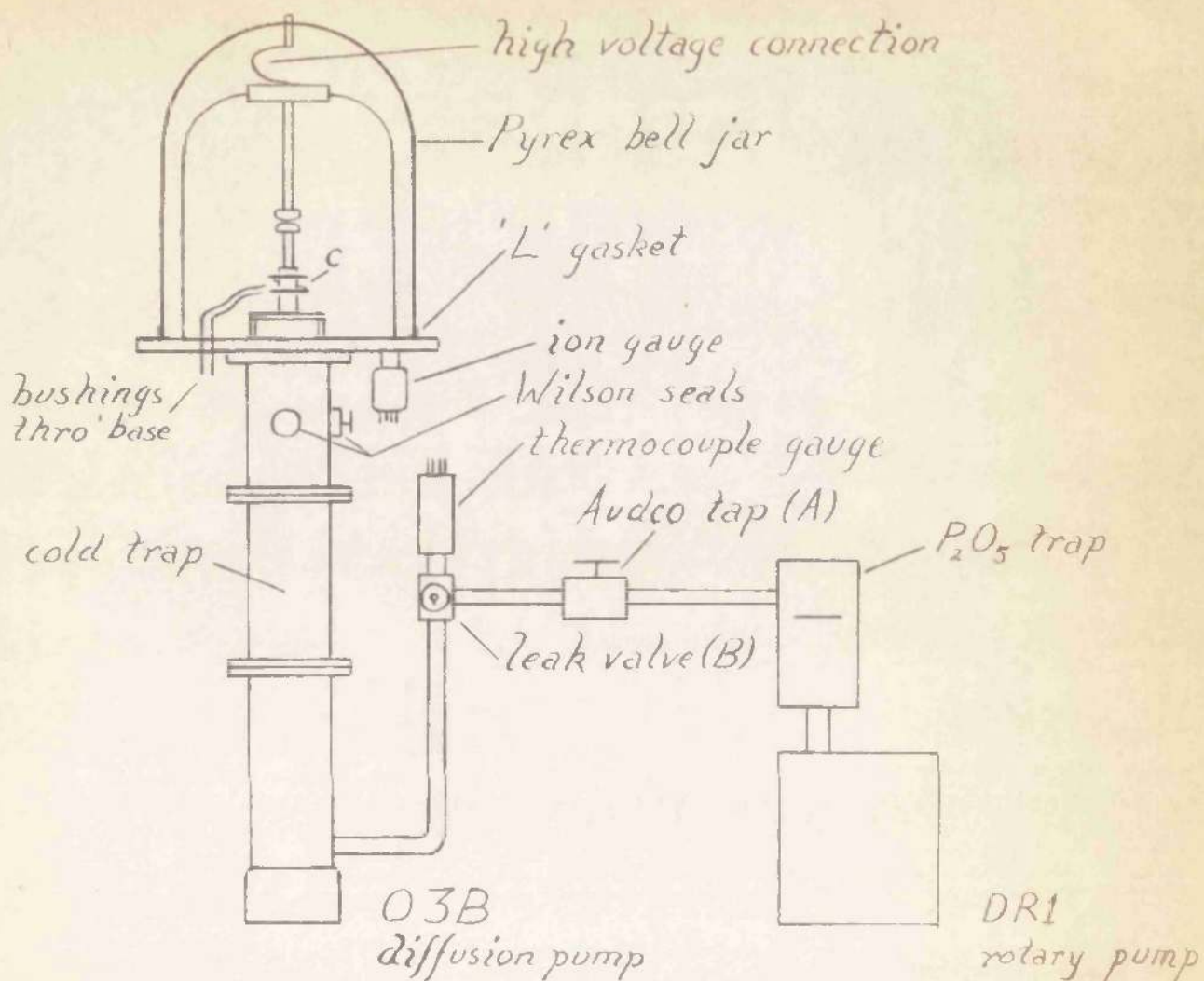


fig 1 High Vacuum System

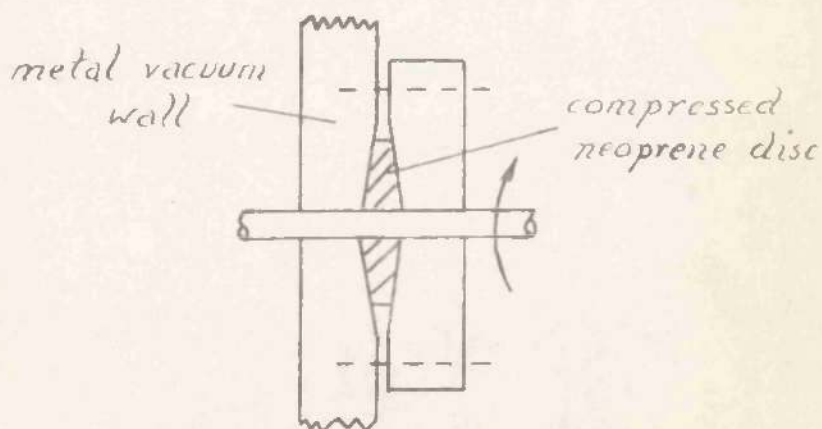


fig 2 Wilson Seal

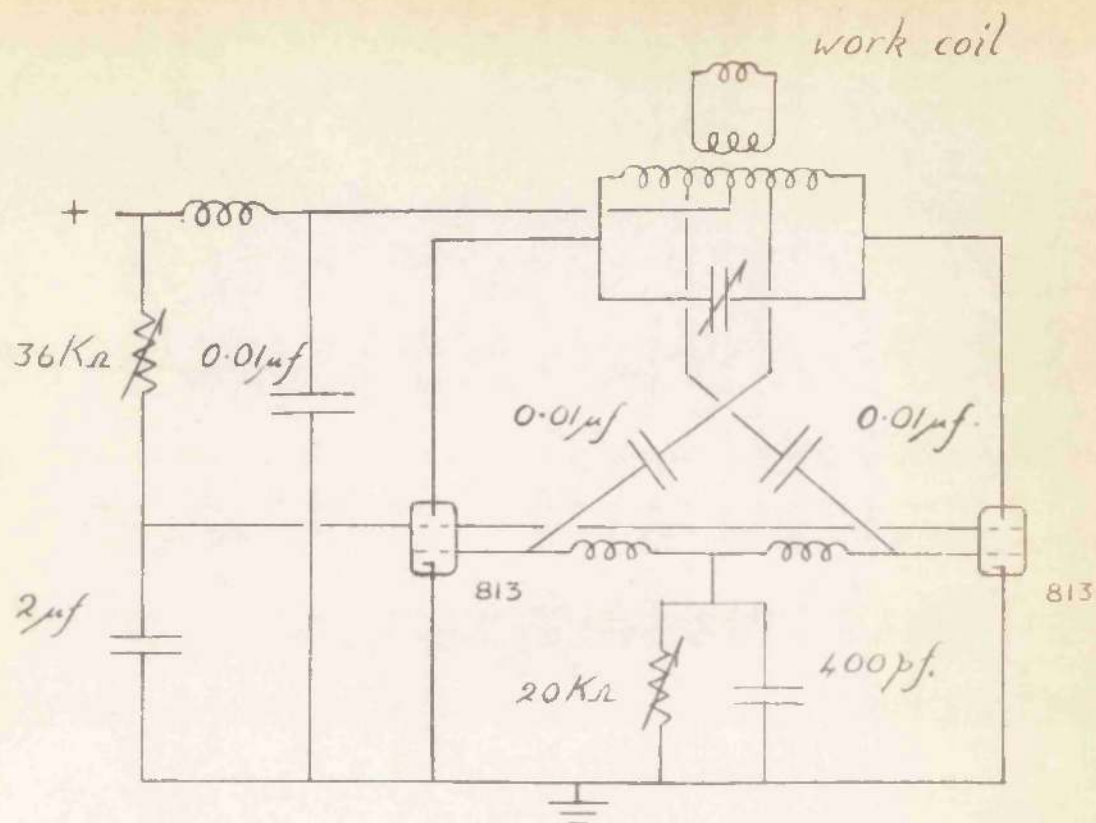


fig 3 Induction Heating Equipment

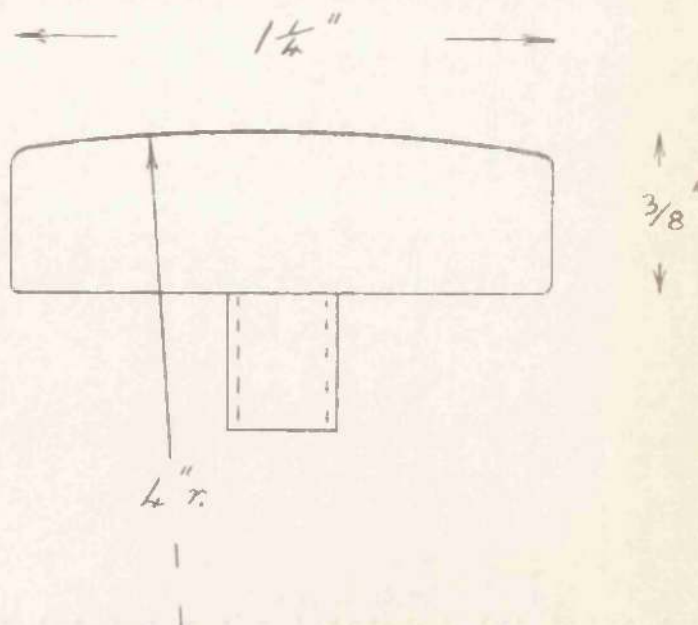


fig 4 Electrode Profile

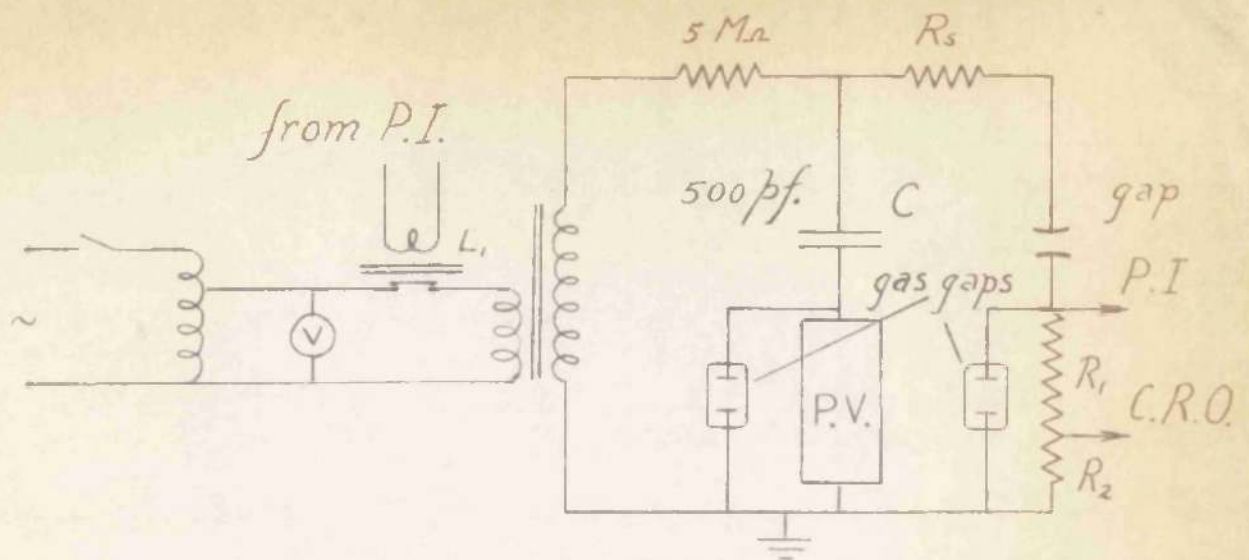


fig 5 High Voltage Circuit

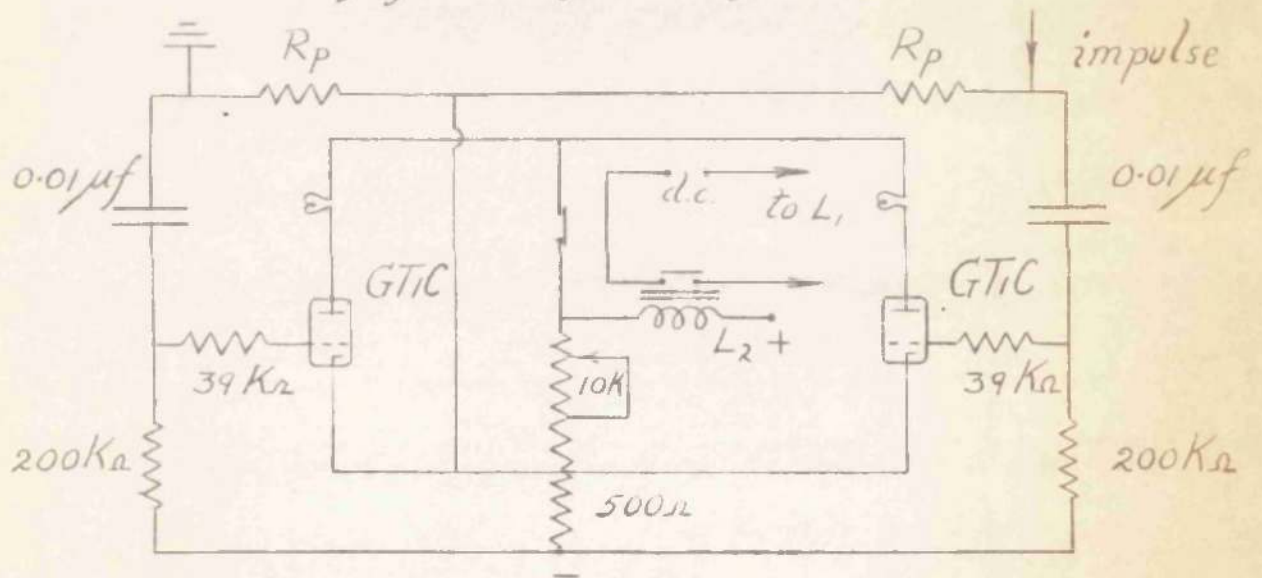


fig 6 Polarity Indicator

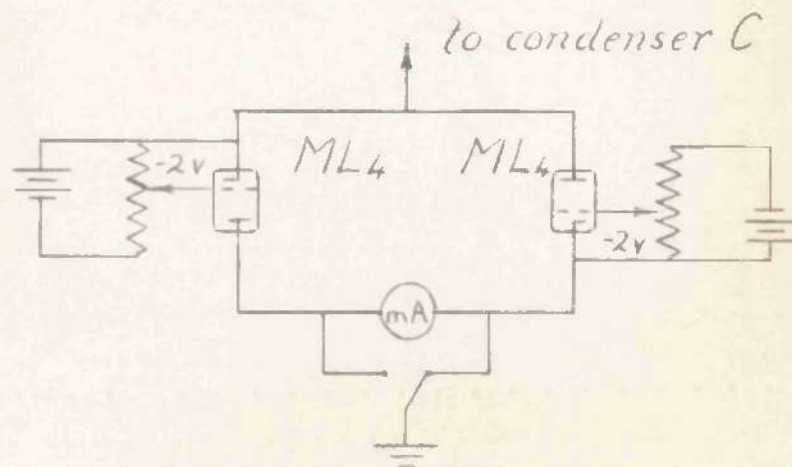


fig 7 Peak Voltmeter

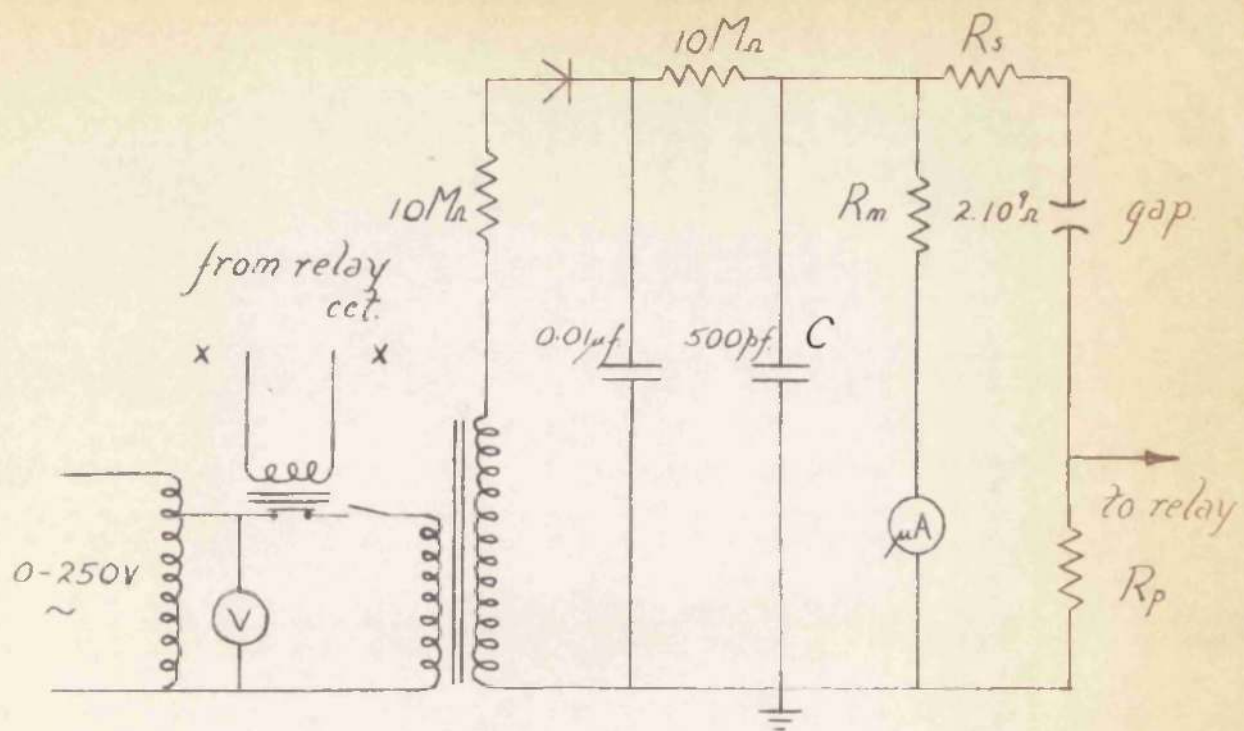


fig 8

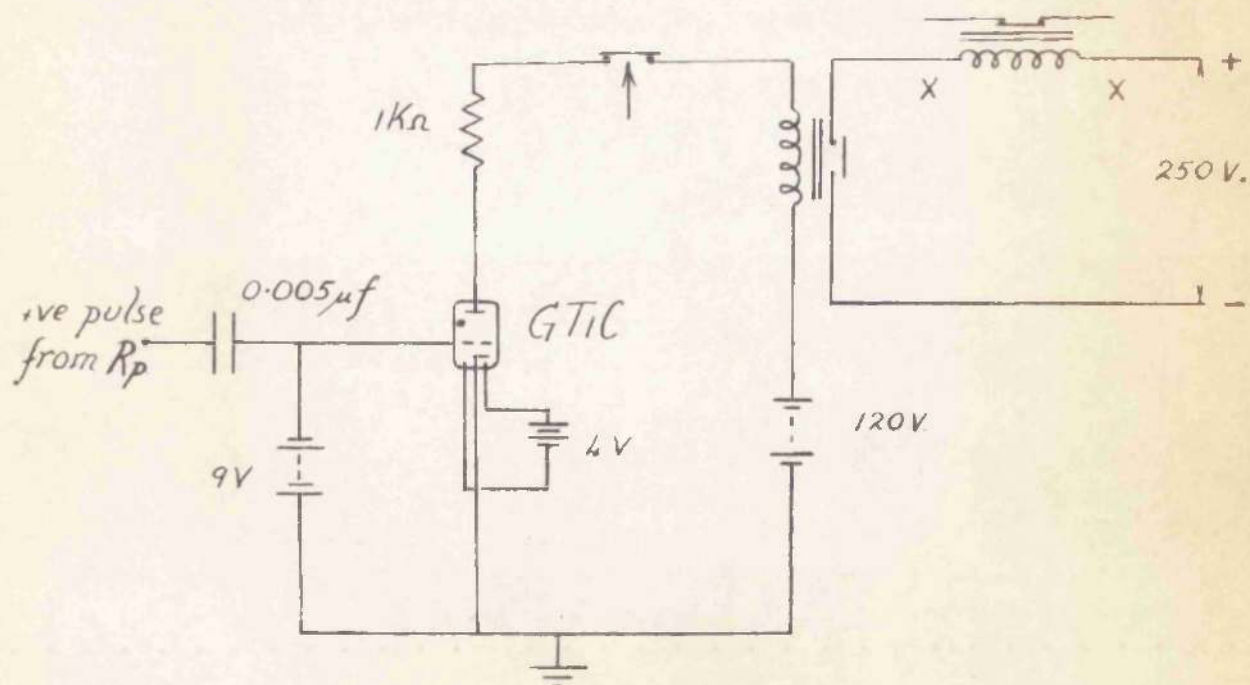


fig 9

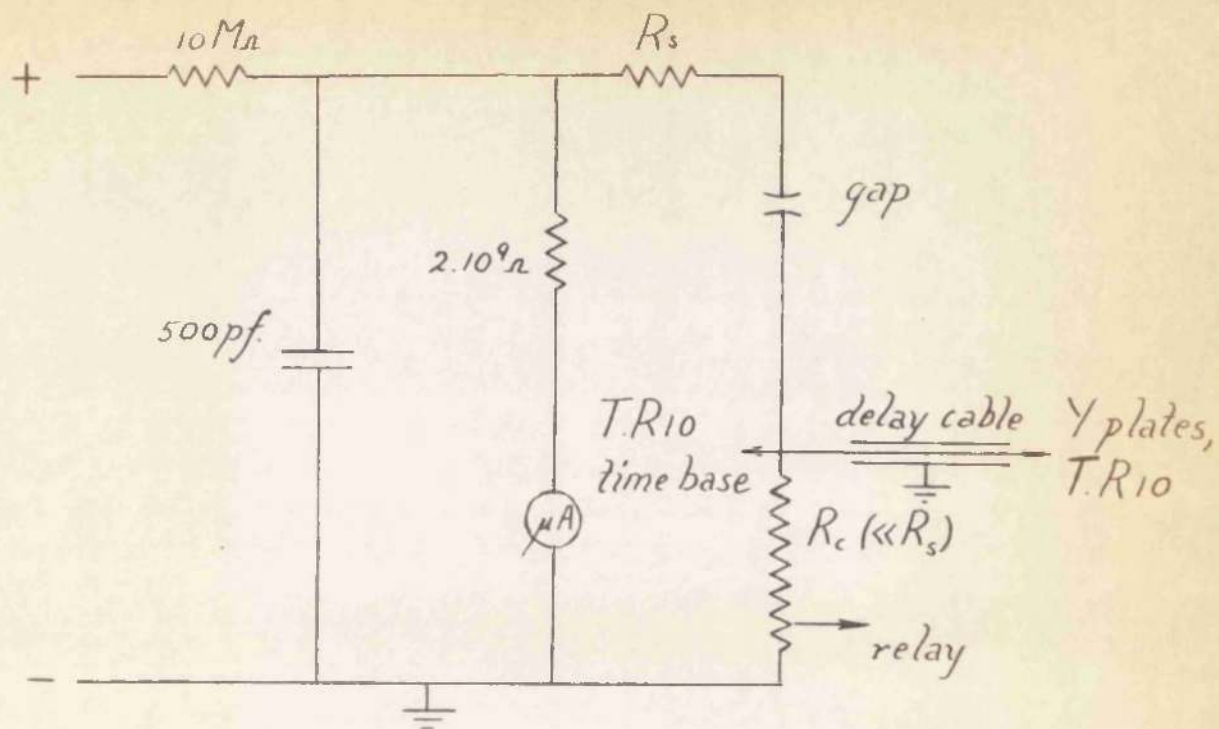


fig 10

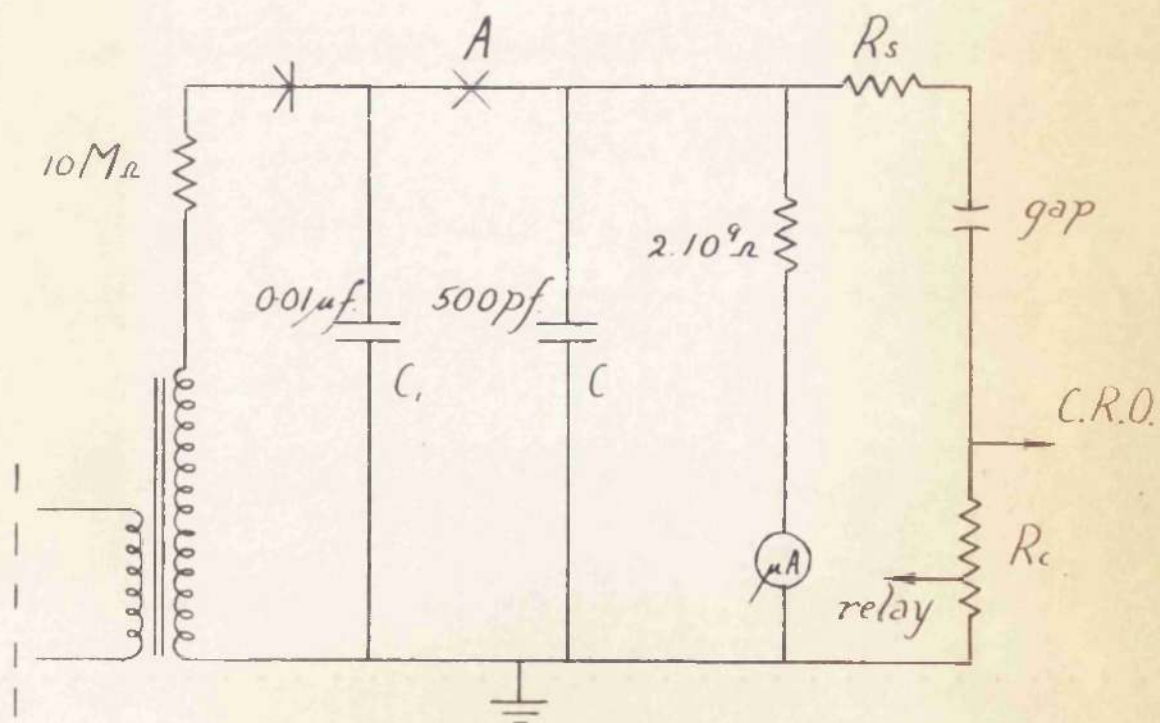


fig 11

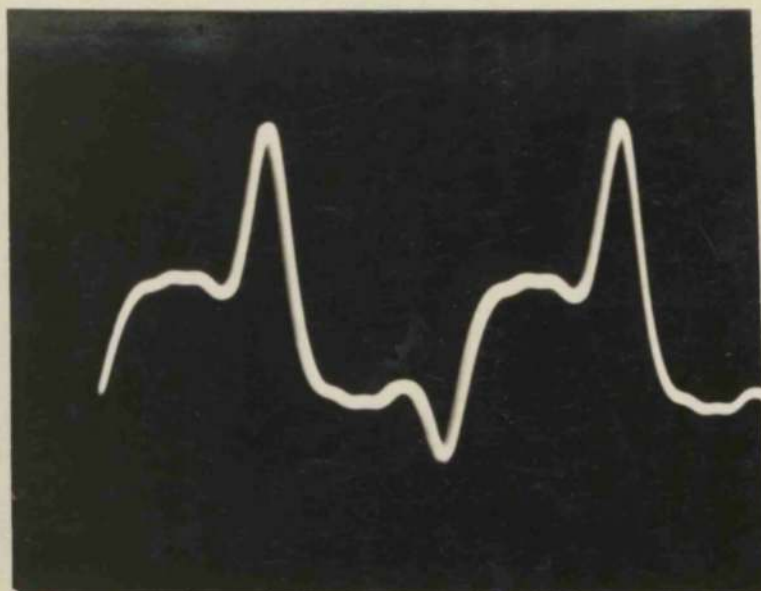


Plate 1 - Field emission superimposed on capacitance current - rough steel electrodes.

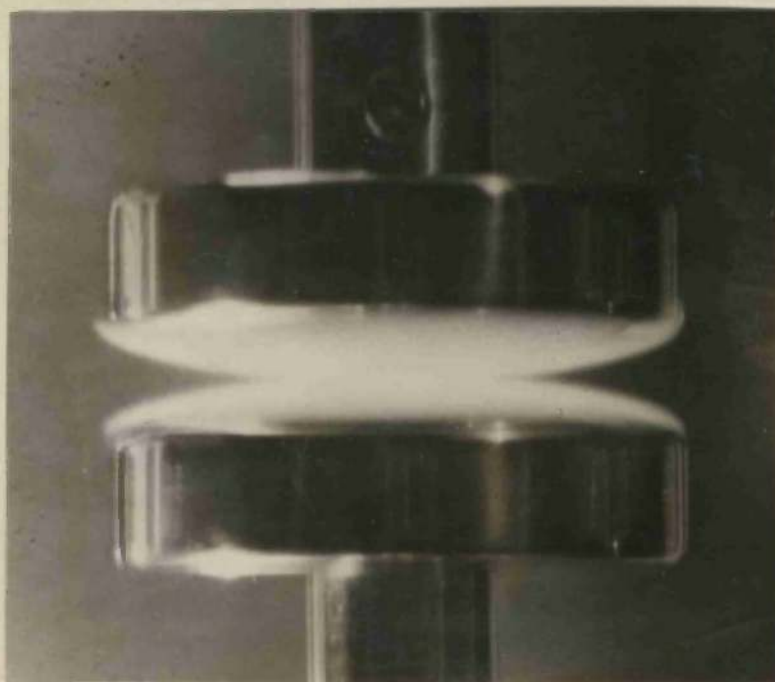


Plate 2 - Glow discharge conditioning.



Plate 3 - A typical cathode mark. $\text{Mag}^n \cdot \times 630$
 Steel electrodes, gap 0.5mm. $R_s = 500 \text{ K}\Omega$

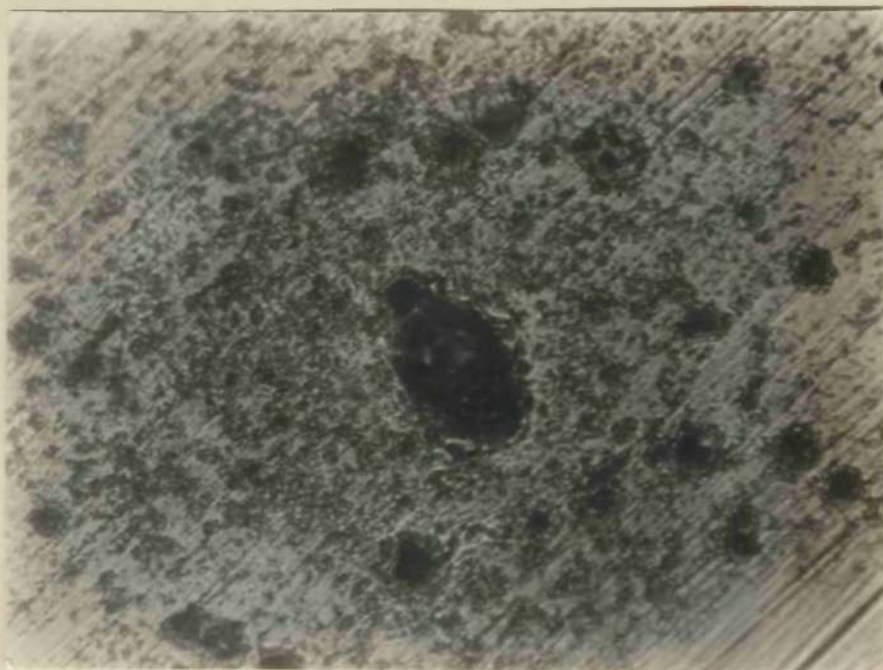


Plate 4 - A typical cathode mark. $\text{Mag}^n \cdot \times 630$
 Steel electrodes, gap 0.5mm. $R_s \rightarrow 0$

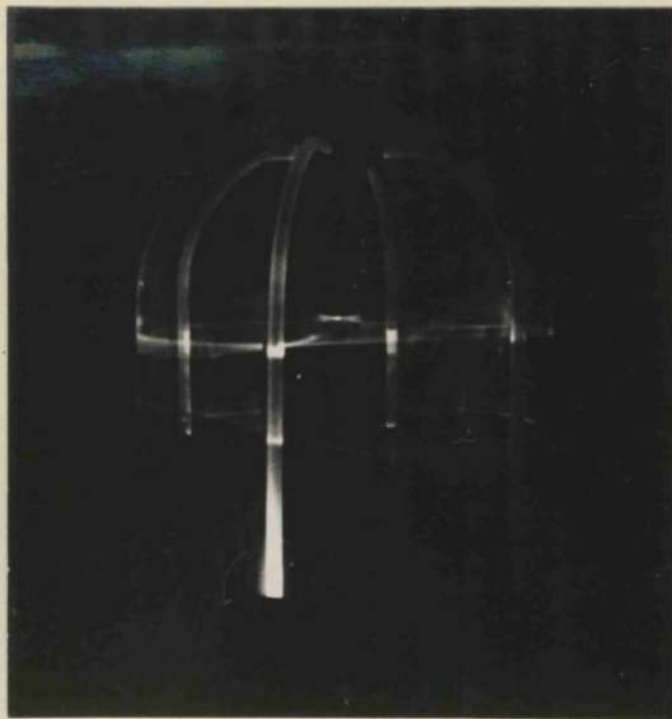


Plate 5 - The Glow Phenomena. Copper electrodes, gap 1mm. $R_s = 11K\Omega$ (Combined effect of a number of glows occurring about 70KV.)

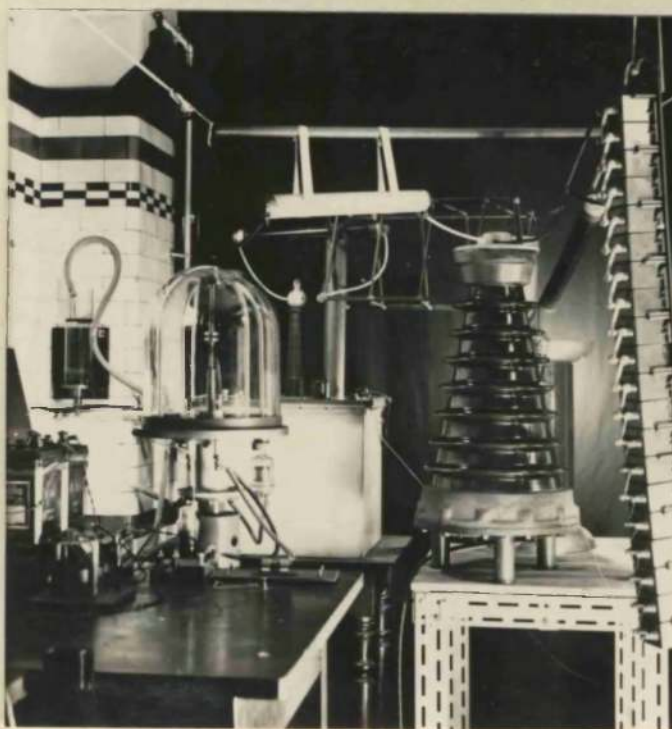


Plate 6 - The equipment for the D.C. study.

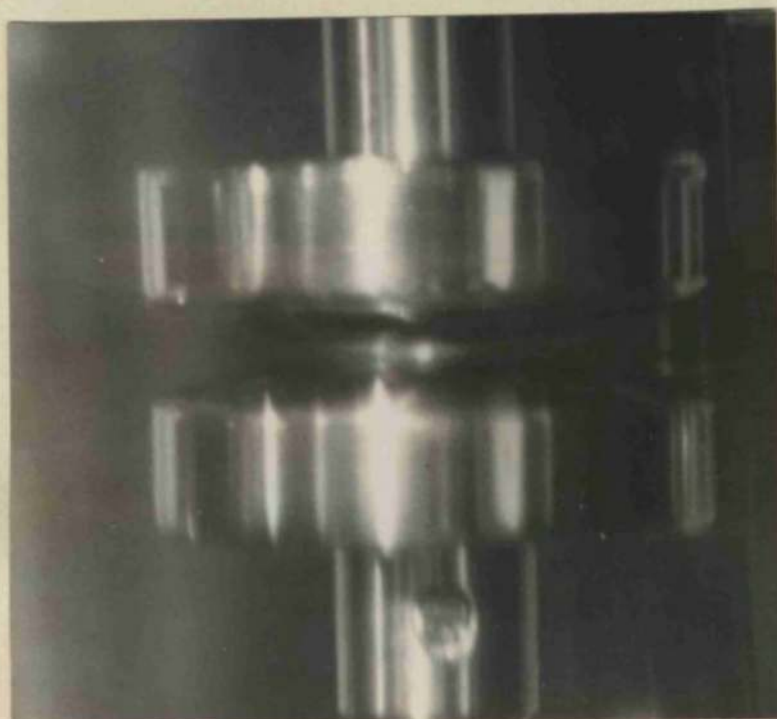


Plate 7 - A spark Breakdown at 51 KV Steel electrodes,
gap 0.5mm. $R_s = 100 \Omega$

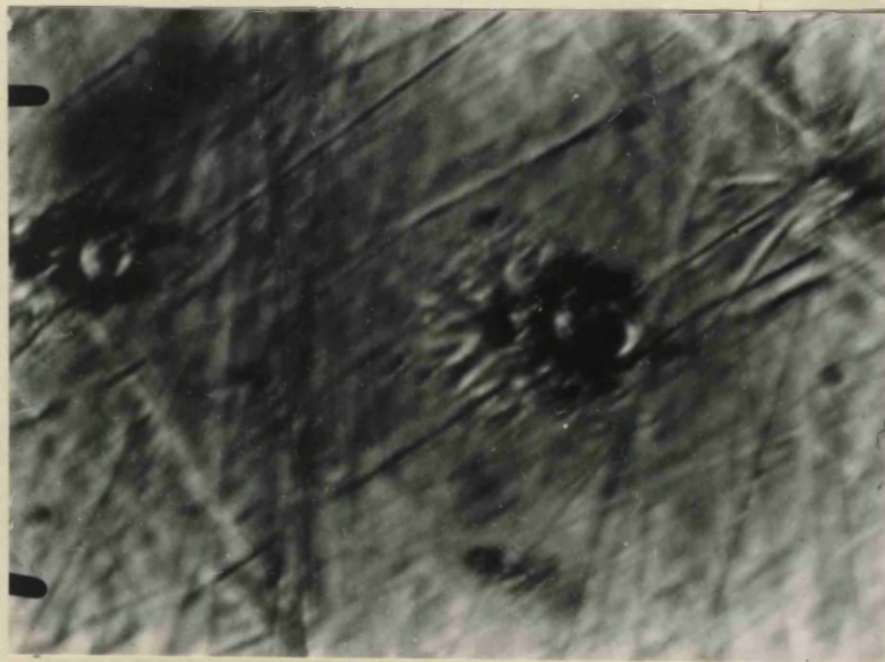


Plate 8 - Typical cathode marks. Mag^{n.} x 1300.

Steel electrodes, gap 0.5mm. $R_s = 100\text{ K}\Omega$

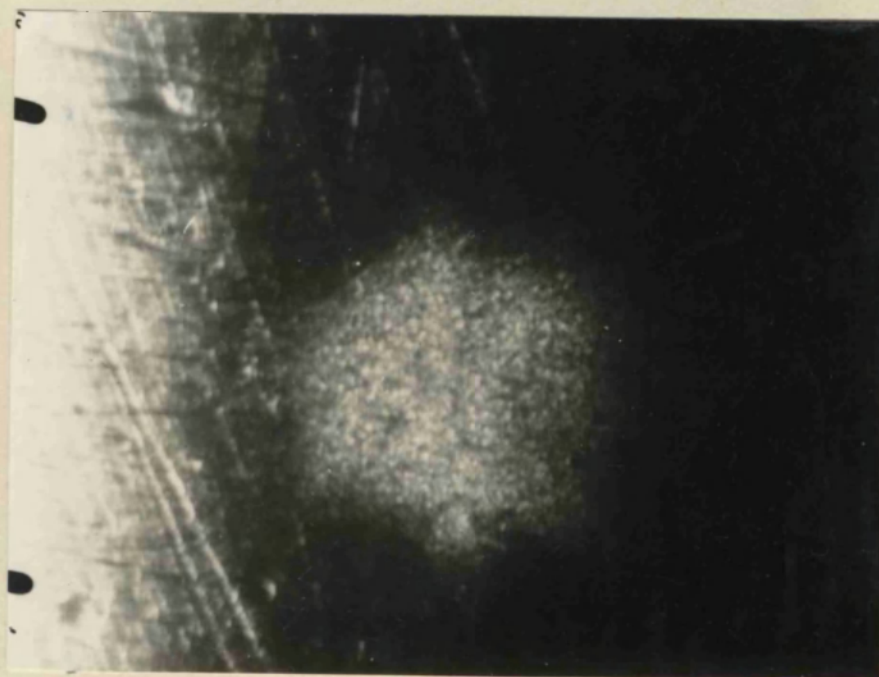


Plate 9 - A typical anode mark. Mag^{n.} x 70

Steel electrodes, gap 0.5mm. $R_s = 100\text{ K}\Omega$

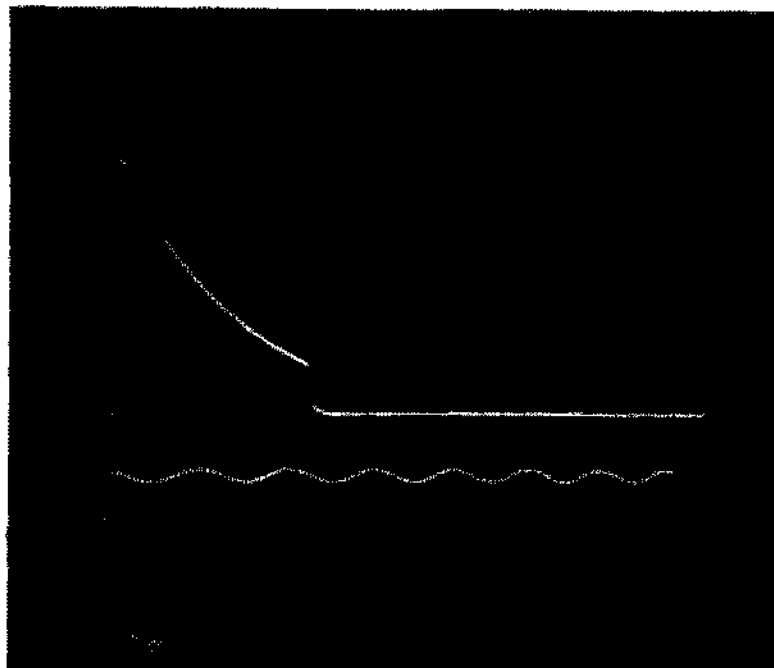


Plate 10 - Spark current at 58.2 KV

(5.0 amp. peak, 0.95 amp. chop.) 0.2 Mc/s Oscⁿ.

Copper electrodes. gap 1mm. $R_s = 11 K\Omega$

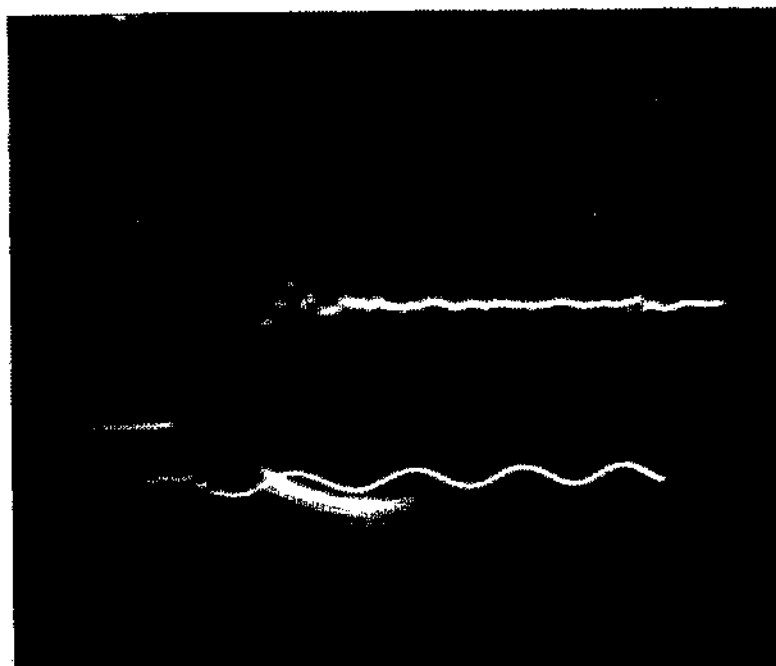


Plate 11 - Spark current at 24.7 KV (2.24 amp. peak)

5.0 Mc/s Oscⁿ.

Steel electrodes. gap 0.2mm. $R_s = 11 K\Omega$



Plate 12 - Suppressed Spark Current at 44.5 KV.

5.0 Mc/s. Oscⁿ.

Steel electrodes, gap 0.5 mm. $R_s = 450 \text{ K}\Omega$

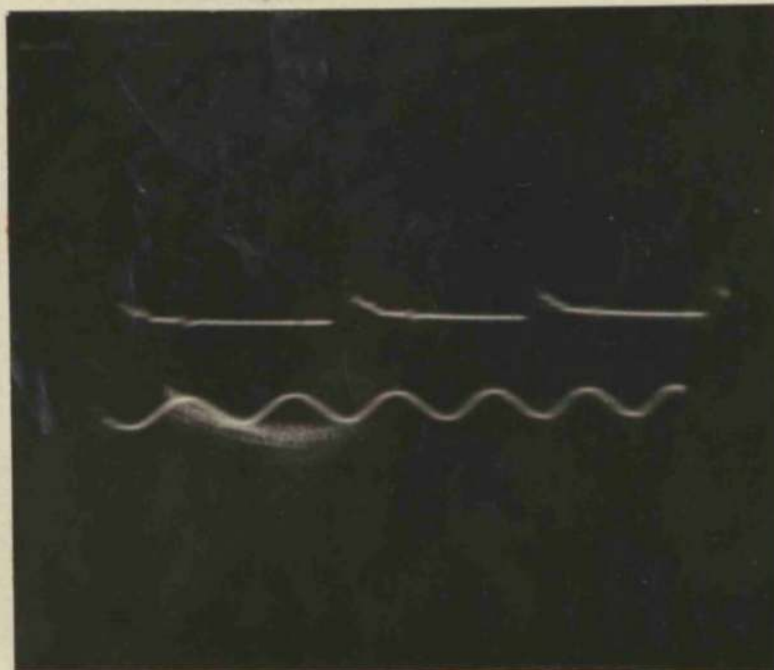


Plate 13 - Spark current - suppressed discharges at

45 KV. approx. 1.0 Mc/s. Oscⁿ.

Steel electrodes, gap 0.5 mm. $R_s = 450 \text{ K}\Omega$

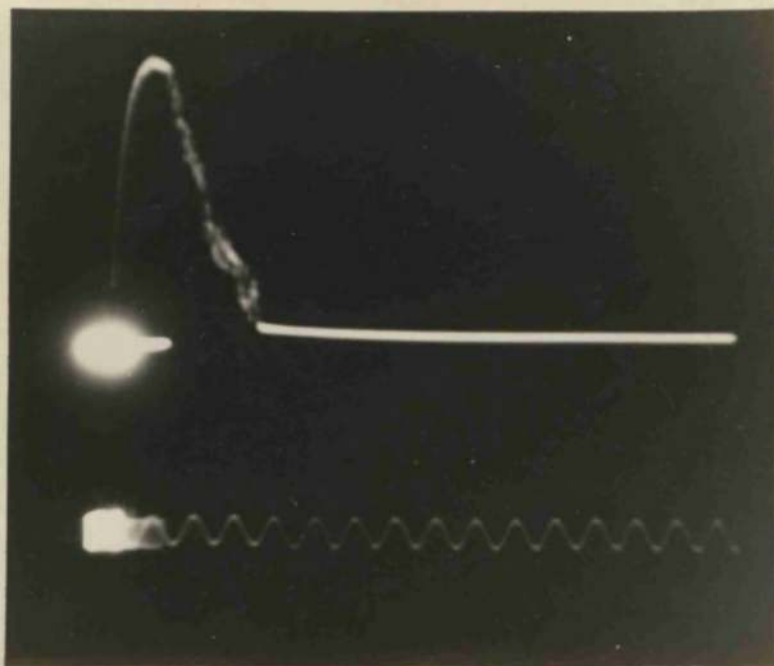


Plate 14a - Glow current at 60 KV. (1.2 m. amp. peak)
 500 c/s. Oscⁿ.
 Copper electrodes. gap 2.0mm. $R_s = 100 \text{ K}\Omega$

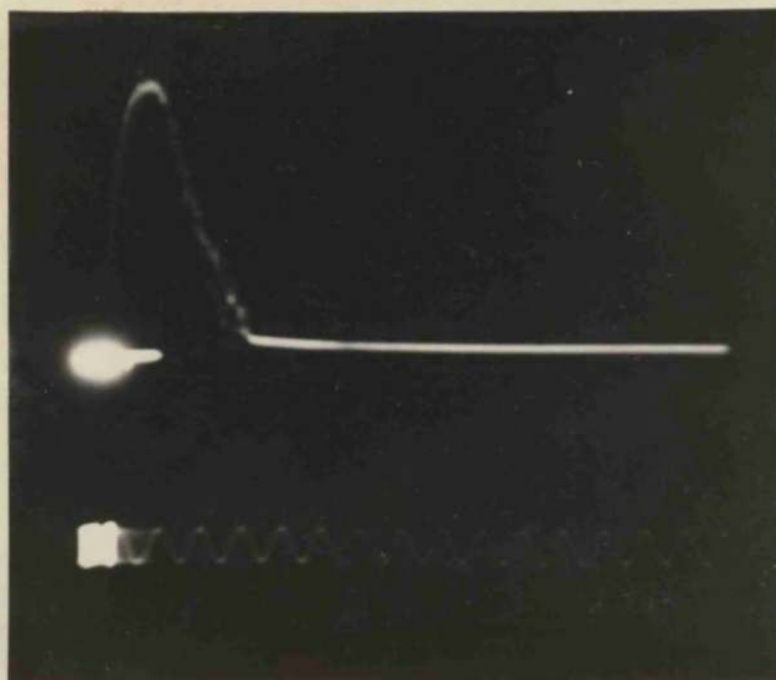


Plate 14b - Glow current at 61 KV (1.15 m. amp. peak)
 500 c/s. Oscⁿ.
 Copper electrodes. gap 2.0mm. $R_s = 100 \text{ K}\Omega$